THE NUTRIENT MICROGRID: ECOLOGICALLY-INSPIRED DESIGN OF URBAN MATERIAL CYCLING NETWORKS

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THE NUTRIENT MICROGRID: ECOLOGICALLY-INSPIRED DESIGN OF URBAN MATERIAL CYCLING NETWORKS

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LIST OF SYMBOLS AND ABBREVIATIONS

ACE	Agri-Network Centralization Experiment
AMI	Average Mutual Information
ASC	Ascendancy
AMR	Atlanta Metropolitan Region
BSF	Black Soldier Fly Larvae
C	Connectance
C_N	Network Centralization
CW	Constructed Wetlands
DC	Development Capacity
ENA	Ecological Network Analysis
FCI	Finn Cycling Index
FW	Food Web
FWF	Farmland Weighting Factor
G	Generalization
L	Number of Links
L_D	Linkage Density
MPL	Mean Path Length
NoM	Nutrient Optimizing Module

$n_{predator}$	Number of Predators
n_{prey}	Number of Prey
$n_{s\text{-}predator}$	Number of Specialized Predators
P_R	Prey to Predator Ratio
P_S	Fraction Specialized Predators
R	Robustness
TSO	Total System Overhead
TST	Total System Throughflow
TST_P	Total System Throughput
$\lambda_{\max}$	Cyclicity (maximum eigenvector)

SUMMARY

Engineered systems are composed of multiple interconnected networks that produce, process, and dispose of waste materials. However, to achieve process efficiency within system boundaries, engineers have historically designed supply chains that are highly centralized and modeled them with surroundings of infinite material sources and sinks. Considering the dwindling resources and growing pollution brought on by this design strategy, this thesis focusses on the material dynamics of the human food supply and waste management infrastructure to identify possible improvements to the material efficiency of these engineered systems. Case studies tracing material through selected urban and industrial networks are presented, and emerging biotechnologies, including aquaponics and constructed wetlands among others, are then introduced to these networks as material cycling modules. These reimagined material networks are then analyzed using ecological and sustainability metrics and compared to the original networks to assess impact and efficiency. Results suggest that a design strategy that employs higher degrees of nutrient cycling, catalyzed by ecologically-inspired material cycling modules, can improve material efficiency and increase the resilience of these systems. Results also suggest that a decentralized urban agriculture network may be more fragile to disruption, with highly specific food sourcing and confined flow paths that do not allow for restructuring in the event of a perturbation.

CHAPTER 1. INTRODUCTION

Urban material infrastructure systems are designed to meet the needs of the urban population. Some systems supply drinking water, food, and energy to the residents and businesses, and then others collect, treat, and dispose of wastes to keep the population safe from the spread of disease. As a network or "web" of subsystems, a diverse set of interconnected, interdependent, and adaptive actors (citizens, industries, and governments among others) interact with one another to exchange materials and energy, in many of the same ways that different species interact within naturally-occurring food webs (Grimm, Morgan Grove et al. 2000, Janssen, Bodin et al. 2006). This complex urban infrastructure produces a type of "infrastructure ecology" characterized by unpredictability, resilience and robustness, non-linearity, and bottom-up emergence (Pandit, Lu et al. 2015, Wilson 2015). Many scientists assert that, because of this emergence in human systems, ecological principles can be applied to engineered systems to increase efficiency through the intelligent use of energy and resources while reducing waste (Odum 1969, Reap 2009, Chen, Fath et al. 2010, Layton, Reap et al. 2012, Chen and Chen 2015, Layton, Bras et al. 2015, Layton, Bras et al. 2016).

Researchers recognize the potential to increase material and energy efficiency through the translation of ecological principles into organizing strategies for human systems (Odum 1969). The purpose of this study is to examine the ways in which ecological network metrics can inform the design of more sustainable, efficient urban food and waste infrastructure systems. Using this ecological approach, Section 1.1 illustrates the disconnect between engineered systems in their current iteration and the ecological precedent set by nature and suggests opportunities to synthesize symbiotic human systems to create ecologically-inspired food systems. Section 1.2 then provides an overview of this thesis and its objectives and organization.

1.1 Motivation

Engineered systems, such as those that produce food and dispose of wastes, have been designed to satisfy the functional requirements of humans, but they often cause unintended consequences to neighboring ecosystems. These systems have historically been designed to achieve process efficiency within system boundaries and been modeled with surroundings of infinite material sources and sinks. Engineers have introduced different methods to manage these consequences, both upstream via material selection and supply chain management, and downstream in end of life scenarios. For example, some engineers employ a strategy to account for a product's "cradle-to-grave" impacts known as Design For Life Cycle (Alting 1995). However, many of the sustainable alternatives still manifest in stark contrast to the natural cycling and efficiency, adaptability, and symbiotic multi-functionality found in natural food, or trophic, systems (Weissburg and Yen 2007, Glier, Tsenn et al. 2011).

Human systems can often benefit by borrowing structures and functions from nature (Benyus 2002, Reap 2009, Glier, Tsenn et al. 2011), which Vogel (1999) calls "biomimetic engineering." This impulse has inspired engineers to embrace biologically-inspired design and has resulted in products that mimic organisms' structures or functions in nature, such as Velcro (Benyus 2002). Within the bioinspired design community, some have looked to ecosystems for their *bio-inspiration* (Bodini, Bondavalli et al. 2012, Layton, Bras et al. 2015, Layton, Bras et al. 2016). By leveraging an ecosystem-inspired approach to systems design, practitioners are often able to achieve improved sustainability by finding synergies with neighboring industries and using waste as inputs to complementary processes (Reap, Baumeister et al. 2005). With this systems-level approach in mind, some engineers have looked for functional emergence or patterns using network analysis in an effort to understand how to better analyze the sustainability of human systems (Bodini, Bondavalli et al. 2012, Layton, Reap et al. 2012, Kharrazi, Rovenskaya et al. 2013, Pizzol, Scotti et al. 2013, Lu, Chen et al. 2015, Layton, Bras et al. 2016).

1.1.1 Ecologically-Inspired Systems Analysis

One type of network analysis, known as Ecological Network Analysis (ENA), is a quantitative tool used by ecologists to study interactions within ecosystems in a holistic manner (Finn 1976, Ulanowicz 1986). ENA food webs provide graphical depiction of the linkages between actors within a given ecosystem with respect to materials and energy. ENA graphs consist of nodes and edges that represent predator-prey exchanges of material and energy. Ecologists use this representation to generate an array of metrics, seeking to understand the links between ecosystem structure and the resulting behaviour of these ecosystems (Fath and Halnes 2007). These metrics describe a natural ecosystems topology, and their embedded functional relationships, characterized by predator-prey interactions (Roberts 1976, Yodzis 1980).

This ecological lens can be applied to human engineered systems, where material and energy flows embody the physical bridge between industrial and natural systems (Bailey, Allen et al. 2004). ENA assists to evaluate engineered system topologies and actors to identify deficient functions and pathways (Layton, Reap et al. 2012, Layton, Bras et al. 2016). It can be used to evaluate engineered industrial systems by translating functional roles found within mature natural ecosystems into industrial system components and then using properties of natural ecosystems to benchmark the performance of these systems (Layton, Reap et al. 2012, Layton, Bras et al. 2016). In this manner, ENA has also been used to characterize urban and industrial material networks (Zhang, Yang et al. 2010, Layton 2014, Zhang, Liu et al. 2014, Chen and Chen 2015, Lu, Chen et al. 2015). These studies suggest that there is an overabundance of consumers and a detriment of producers and recycling actors within engineered material networks. Since technology often moves at a pace that outstrips municipal development, ENA's analytical tools provide a way to identify what technological solutions should be developed or augmented by identifying linkages or functions that would improve network metrics (Malone, Cohen et al. 2018). However, this type of analysis has only been done on existing urban and industrial networks or on a few potential water and industrial networks (Bodini and Bondavalli 2002, Layton, Bras et al. 2017), but it has not yet been used as an approach to design new urban food networks.

1.1.2 Industrial Agriculture and its Discontents

Human activity now dominates nearly all of Earth's biogeochemical and ecological cycles (Vitousek, Mooney et al. 1997), and industrial food production systems in their current iteration contribute significantly to the environmental burden of human activity. For example, The European Commission found that food products are responsible for 20-30% of the environmental impacts of consumption. Some of the heavy penalties brought on by increased agricultural productivity have been the water pollution, smog and acid rain, global warming, and other associated environmental impacts of artificial nitrogen fixation (Kaye, Groffman et al. 2006). On account of this nitrogen mismanagement, The National Academy of Engineering cited improved nitrogen cycle stewardship as one of 14 Grand Challenges for Engineering for the 21st century (Mote, Dowling et al. 2016).

1.1.2.1 The Not-So-Green Revolution: Chemical Fertilizer

In nature, one species' waste is food for others in their ecosystem (Moore, Berlow et al. 2004). By contrast, high-yield activities typical of industrialized agriculture have been made possible by artificially-derived fertilizers as their source of nitrogen, deviating from the natural example where plants use nitrogen waste products from other organisms (Smil 1997). These fertilizers are synthesized using natural gas, or methane, largely from fossil origin (Dawson and Hilton 2011). Fossil fuels also contain nitrogen, which is released in the form of N oxides (NO_x) and other compound forms when it is used as the energy source for fertilizers. Land application of manure and fertilizer is also responsible for atmospheric emissions of ammonia (NH_3), as 7% of the chemical fertilizer applied to cropland is then lost to the atmosphere as NH_3 volatilizes (Liang, Chen et al. 2007). Additionally, because conventional agriculture is an open system, water and nutrients are often used in excess (Walker and Beck 2011) and drain from agricultural sources into local waterways, subsequently increasing runoff and nutrient leaching. This excess nutrient flux into waterways nourishes algae, which in turn consume dissolved oxygen and throw off the balance of existing ecological activity. Algae overgrowth, also known as eutrophication, causes anoxic areas, or "dead zones," in these waterways and starves other wildlife of this precious resource (Cabrera and Gordillo 1995, Smil 1999, Killebrew and Wolff 2000).

In addition to the downstream environmental impacts caused by fertilizer application, there are severe upstream costs incurred through artificial fertilizer use, including a steep energy cost. Ammonia production, the primary stage of the synthetic production of N fertilizers, requires about 1,100 m^3 of natural gas per metric ton of anhydrous ammonia produced. As much of the crop grown in industrial agriculture is then fed to livestock, the ammonia nitrogen from artificial fertilizers eventually produces roughly 50% of all the protein nitrogen required today (Liang, Chen et al. 2007, Dawson and Hilton 2011).

1.1.2.2 The High Cost of Human Protein Consumption

Global demand for protein is also at an all-time high as standards of living rise in the developing world (Dawson and Hilton 2011). In the oceans, overfishing has driven aquatic populations of some commercial fish, such as mackerel and tuna, down by nearly 75% (Abrami, Bernard et al. 2015). On the land, an increase in livestock density has increased the potential for manure applications in industrial livestock operations to exceed the lands' capacity to assimilate nutrients. This results in these nutrients leaching or running off into the local waterways (Harter, Lund et al. 2012). To meet this protein-based demand with less resources, some innovative yet environmentally burdensome solutions have arisen from protein rearing industries such as Aquaculture for fish and close quarter confinement poultry farming.

Aquaculture is an increasingly popular method to farm fish or other aquatic organisms in a controlled environment (FAO 2007). However, this farming method increases the eutrophication burden of food cultivation by flushing nutrient-rich wastewater into surrounding ecosystems. The use of fishmeal in aquafeeds also contributes to significant environmental burden through overfishing in the oceans (New 2002). Furthermore, there is also growing concern in the scientific community that the use of fishmeal as a feed source in the Aquaculture farming method is contributing to the prevalence of antibiotic resistance in bacteria communities found in marine sediments (Han, Wang et al. 2017).

Poultry farming is another popular protein cultivation strategy. Analysis shows that the structure of animal agriculture has changed drastically over the last 30 years. Large industrial operations have replaced small and medium farms, and relative confinement has increased. This confinement has led to a shift in animal populations, with a decline in cattle rearing and an increase in poultry populations (Kellogg, Lander et al. 2000). Along with aquaculture, fishmeal is also a major source of food in the poultry industry, compounding the environmental burden. In the United States, the state of Georgia accounts for over 8.5% of the nation's confined poultry operations (Kellogg, Lander et al. 2000).

1.1.2.3 Local Food Movement

Urban agriculture, or the idea of bringing food cultivation closer to the site of consumption, has been suggested as a strategy to mitigate some of the resource use and efficiency challenges introduced by these large-scale, centralized, industrial agriculture operations (Thomaier, Specht et al. 2015). The idea surrounding urban agriculture arises from studies that indicate that the average meal contains ingredients from at least five different foreign nations (NRDC 2007), and the average piece of produce is shipped 1,500 miles (2,414 km) before it reaches the plate (DeWeerdt 2009). Urban agriculture has recently garnered interest across many academic communities, including policy, economics, and urban ecology (Chiffoleau and Touzard 2014). It has been suggested that urban agriculture could reduce “food miles,” or the environmental burdens of long-distance travel via climate-controlled, energy-intensive shipping infrastructure (Feenstra 2009).

However, the burden of these food miles identified through life cycle impact analyses suggest that the benefits of local production on climate change may be dwarfed by burdens such as land use and nitrogen mismanagement (Weber and Matthews 2008). Indeed, a recent obsession within the sustainability community has given rise to the “hyperlocal” food movement, which often trades food mile impacts for those wrought by over-designed products that are only available to the ultra-wealthy (DeLind 2010, Born and Purcell 2016). These problems and potential solutions lead to a necessity for evaluating the net impacts of urban farming on the food system and the determination of the appropriate scale at which urban agriculture should be implemented. The insight gained by quantitative modelling of the urban agricultural system could allow for avoiding the pitfalls of a hasty solutions that may result in unintended consequences.

1.1.3 Down the Drain: Modelling Waste Management as a Missed Opportunity

In addition to providing food for its populations, urban food systems are also responsible for the treatment of the solid and liquid “wastes” produced by these populations. Many researchers assert that this current paradigm to treat human food and biological biproducts as “waste” is a negligent oversite (Wilsenach and Van Loosdrecht 2006, Cease, Capps et al. 2015, Wielemaker, Weijma et al. 2016). For example, wastewater treatment systems are originally designed to process wastewater and solid organic wastes

(Tchobanoglous, Burton et al. 1990, Anderson, Rosemarin et al. 2016) and remove these contaminants from water, often viewing nitrogen as a burden rather than a potential resource (Karak and Bhattacharyya 2011). Much like the agricultural systems discussed previously, aqueous nitrogen is then discharged by wastewater treatment facilities into the water basins, resulting in algal blooms, aquatic hypoxia, and anoxia that kills fish (Van Drecht, Bouwman et al. 2009). Instead of viewing nitrogen as a burden, one can see how natural systems fully utilize the nutrient as a resource for plant growth (Singh and Bakshi 2013, Trang and Brix 2014, Zhang, Chen et al. 2014).

The natural ecosystems, in contrast to human engineered systems, have little to no material waste, as one species' biproducts are food for others in the ecosystem (Odum 1969, Ulanowicz 1983, Patten, Higashi et al. 1990). Inspired by the material efficiency and cycling of natural ecosystems, emerging studies suggest that more can be done to reduce the harmful agriculture and waste management practices described previously while also reducing costs (Karak and Bhattacharyya 2011, Iatrou, Stasinakis et al. 2015, Simha and Ganesapillai 2017).

1.1.4 Summary of Motivation

Demands for efficient and resilient food production and waste management infrastructure will increase in coming decades due to population growth, climate change and other factors. Humans have constructed agricultural systems to try and meet demands for protein such as aquaculture, but these systems are linear and high in waste, leading to environmental burdens such as overfishing in the oceans. Waste management solutions in urban settings have been designed in a similar manner, contributing to environmental issues such as eutrophication. Both industrial agriculture and wastewater treatment systems, in their current iterations, leave much room for improvement.

Present solutions to these problems are limited, mostly due to a lack of a systems-level understanding and conclusive quantitative analysis. The majority of agricultural and waste management analysis to date has compared unit-processes or a products development rather than providing solutions from a systems-wide perspective. For example, urban agriculture practitioners in the United States focus on food miles but tend to overlook or oversimplify the need for improved nutrient management (Al-Kodmany 2018). Others have evaluated the impacts of food products on the environment, but they have focused on individual processes or products without evaluating the system in a holistic manner (Weber and Matthews 2008). This unit-process and product-level approach has left many questions unanswered in the field of sustainable agriculture and their effects on urban food systems, such as determining the appropriate scale for production in agricultural systems and the potential of reusing nutrients otherwise thought of as waste. These questions will be addressed in this thesis using the network approach afforded by Ecological Network Analysis.

1.2 Thesis Overview and Objectives

When applied to the human food web, ENA enables theoretical mediation of nutrient flows and the embodied energy and resources used for its cultivation, resulting in a system-wide approach to sustainable systems design (Layton, Reap et al. 2012, Layton, Bras et al. 2016). This thesis applies the same network approach to evaluate existing agriculture and waste management infrastructure actors in the Atlanta Metropolitan Region in the state of Georgia in the United States. This is accomplished by identifying pathways, both industrial and biological, by which one could mediate the flows of nitrogen (N) to reduce waste and emissions. A simplified urban infrastructure model is used to construct several networks of differing interactions between the existing urban food actors in the Atlanta Metropolitan Region. In addition, principles derived from ecology, such as increased cycling, are integrated in these networks to assess the sustainable potentials of select emerging biotechnologies. Each actor within these different network configurations are defined with a set of behaviors, production capacities, and biological efficiencies drawn from literature.

1.2.1 Research Questions

By implementing theoretical structural and functional changes to a simplified human food network, this thesis attempts to answer the following questions:

- How does network performance, as measured by ecological network analysis, differ between systems that import all food and systems where food is sourced from within the system boundary?
- When food is sourced within the system boundary, what level of agri-network centralization produces the most favorable ecological network performance?
- Can a correlation between conventional ENA indices and the degree of food system centralization be established?

- How do ecological network performance, agri-network centralization and embedded life cycle impacts change when biological actors are introduced as nutrient recycling modules?

By manipulating the networks' degree of centralization in the first experiment, this study is one of the first that attempts to understand urban food production from an ecological systems perspective. With the biological actors introduced as nutrient modules in the second experiment, it is also the first study to use ecological principles to suggest and evaluate functional improvements that could be made to an urban food network.

This study's objective is three-fold: first, to identify and model a baseline network of actors and nitrogen flows between them in the Atlanta Metropolitan Region's food network; next, to test the effects of modifying the baseline model to include urban agriculture and vary the level of centralization through topological changes; and third, it introduces nutrient modules as actors to test the network-wide impact of increased nitrogen cycling. These objectives are achieved through two related experiments, described below in Sections 1.2.2 and 1.2.3.

1.2.2 Experiment 1: Agri-Network Centralization Experiment (ACE)

The Agri-Network Centralization Experiment (ACE) tests the hypothesis that decentralized urban agriculture systems are more sustainable from a network perspective than centralized agriculture systems. This hypothesis is tested using the existing infrastructure as actors within the simplified network and flows between them are identified from available data for the Atlanta Metropolitan Region.

Research Task 1a: Constant and Variable Actors and Associated Nitrogen Flows

The first step in the ACE model is to determine the system boundary and the critical actors in the Atlanta Metropolitan Region food system. Actors in this model are divided into two categories: constant actors and independent or dependent variable actors. The constant actors include the zone population, restaurants, wastewater facilities, and municipal solid waste handlers. The constant actors do not change amongst the baseline model or the decentralized urban agriculture models found in this experiment. The independent variable actors include the farming actors, which include the production of poultry and produce. These actors change in the baseline model and the decentralized urban agriculture models with the downstream dependent variables changing as a result. The dependent variable actor in all of the models is the food distribution industry.

Connections and nitrogen flow amounts between these actors in the models were calculated using data from a variety of sources including the United States Department of Agriculture (USDA 2014), literature provided by the Atlanta Metropolitan Water District (AECOM 2009) and the Atlanta Metropolitan Region (Atlanta Regional Commission Research 2010), and commodity distribution studies (MWPVL 2008). Based upon this available data, the actors in the baseline and decentralized models are broken down into either region, county, or zone levels. Population food requirements and waste patterns are calculated to estimate the per capita flows of nitrogen into and out of the population, and regional assumptions were used to calculate flows to waste management actors (Decker, Elliott et al. 2000, Beck and May 2006, FAO 2011, USDA 2012). All of the assumptions and constants used to calculate the nitrogen flow interactions amongst the actors in the baseline and decentralized urban agriculture models are outlined in more detail in Chapter 4.

Research Task 1b: Establish A Baseline Case Study

The data-derived and calculated nitrogen flows into and out of each constant and variable actor from Task 1a were used to establish a baseline case study in which all food is imported, and all agriculture products grown from within the system are exported without consumption by the population. Farmland, poultry, and population data, reported on the county-wide level, were further divided into zones based on the number of wastewater treatment facilities in each county (see Section 4.2). It uses a hierarchical distribution structure for inputs and later collection of outputs based on the average grocery and commodity distribution structure characteristic of industries in the United States (MWPVL 2008, MWPVL 2010). This baseline is known as the Import/Export (IE) Case Study, and it is used as the case study against which each of the subsequent case studies are compared.

Research Task 1c: Urban farm scenarios

Using the system boundary and the actors established in Task 1a and the baseline distribution structure established in 1b, the "Urban farm scenarios" modify the baseline case study into 3 related case studies in which agriculture products grown within the system boundary provide the primary source of food for the population within the boundary. The 3 new case studies are constructed by aggregating farmland and poultry actors established in the baseline into increasingly centralized produce and poultry actors to explore the effects of urban food production and urban agriculture centralization on ecological network performance.

Research Task 1e: Analysis of Case Studies

Following the completion of these 4 research tasks, the following steps are taken:

i. Analyze all 4 case studies using indicators outlined in Chapter 3.
ii. Compare network performance of each to existing natural food webs.
iii. Compare relative environmental impact of imports and waste.

1.2.2.1 Summary of Experiment 1

The ACE uses 4 case studies to model a baseline and urban agriculture network configuration for the Atlanta Metropolitan Region. The objective is to test the hypothesis that more decentralized food networks more closely resemble natural ecosystems. This is accomplished by using these case studies to explore the impacts of varying levels of urban agriculture centralization on overall ecological network performance as compared to a scenario without food procurement from urban agriculture. The variation of farm actor centralization can be seen in Figure 1.

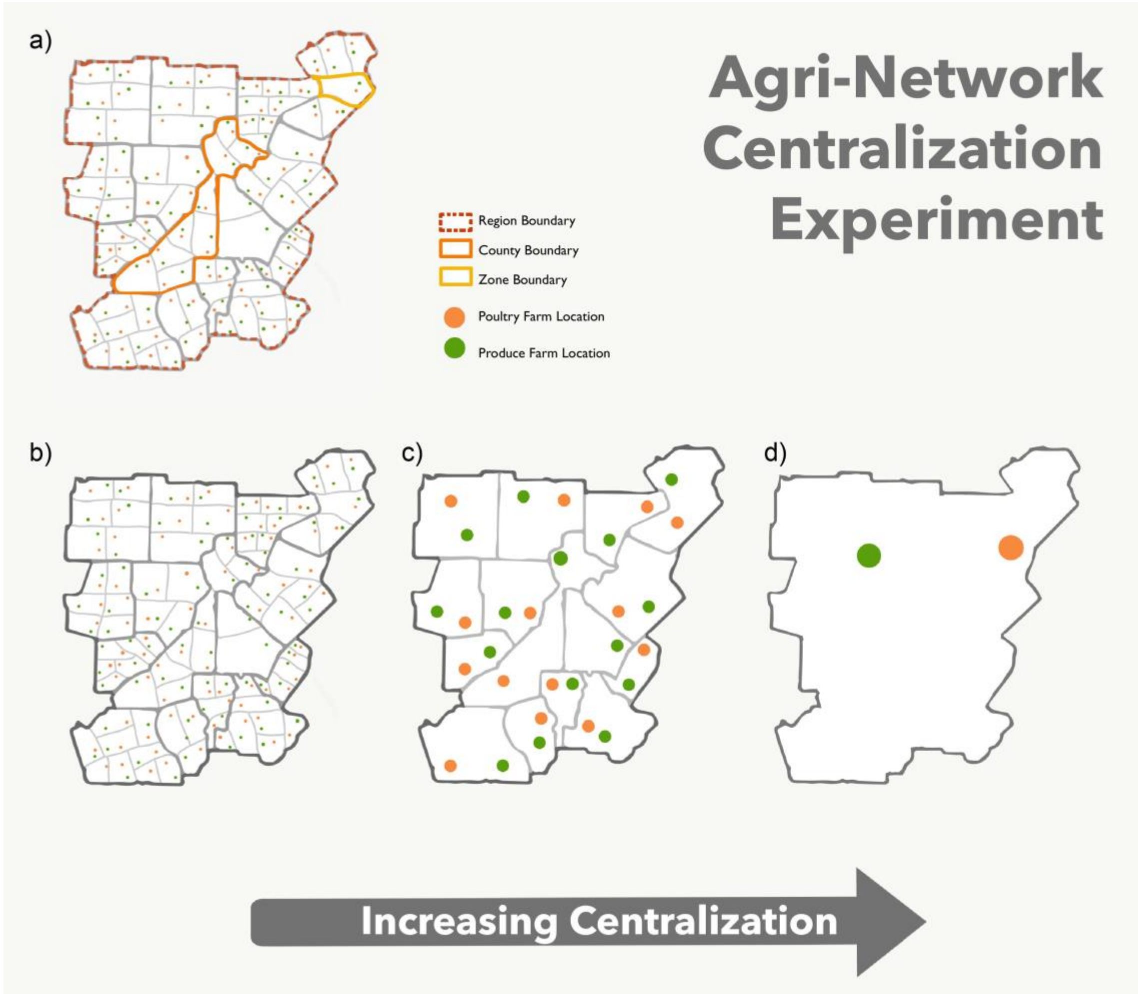


Figure 1: Farm actor locations in each of the Agri-Network Centralization Experiment (ACE) configurations. Poultry farms (orange) and produce farms (green) in baseline Import/Export Case (a) and Zone Urban Farm Case (b) contain farms in each zone. The County Urban Farm Case (c) has farms aggregated more centralized county farms. The Region Urban Farm Case (d) has two large farms serving the entire Atlanta region.

1.2.3 Experiment 2: Improved Cycling Using Nutrient Optimizing Modules (NoM)

Noting the lack of cycling in many urban systems in the case studies presented in Experiment 1, the follow-up Nutrient Optimizing Module (NoM) experiment introduces ecologically-inspired nutrient cycling modules on the zone level as a potential means of mitigating nitrogen waste and material inefficiencies. Building on the methodology presented in Experiment 1 (ACE), the NoM experiment tests the hypothesis that decentralized networks with recycling actors will more closely resemble natural ecosystems than more centralized urban agriculture networks without cycling functional actors.

Research Task 2a: Additional Actors Introduced

Nitrogen waste streams identified in Experiment 1 are rerouted to recycling biotechnology module actors. These actors include black soldier flies (BSF), Constructed wetlands (CW), and Aquaponic Plants and Fish (APP & APF). BSF's can eat a variety of food and human wastes with high nitrogen efficiency (meaning they convert a large percent of feedstock nitrogen to biomass), are introduced in to upcycle food and human waste products (Diener, Solano et al. 2011, Banks, Gibson et al. 2014, Nguyen, Tomberlin et al. 2015). CW's planted with duckweed are introduced to filter wastewater effluent otherwise discharged or land-applied in the baseline model. (Hillman and Culley 1978, Körner and Vermaat 1998). Both BSF and CW provide nutritious feed alternatives to fishmeal (Culley and Epps 1973). APF & APP's are introduced as additional food products due to findings that the combined cultivation of fish and plants provide a more efficient use of nitrogen inputs (Hindelang, Gheewala et al. 2014, Love, Fry et al. 2014, Yogev, Barnes et al. 2016, Cohen, Malone et al. 2018).

Research Task 2b: Modifications of Network from Experiment 1 to form the NoM Network

The new actors introduced in Task 2a are then added to the most decentralized network from Experiment 1 at the zone level. These new actors create material cycling within the network. One of the cycles this process creates is visualized in Figure 2.

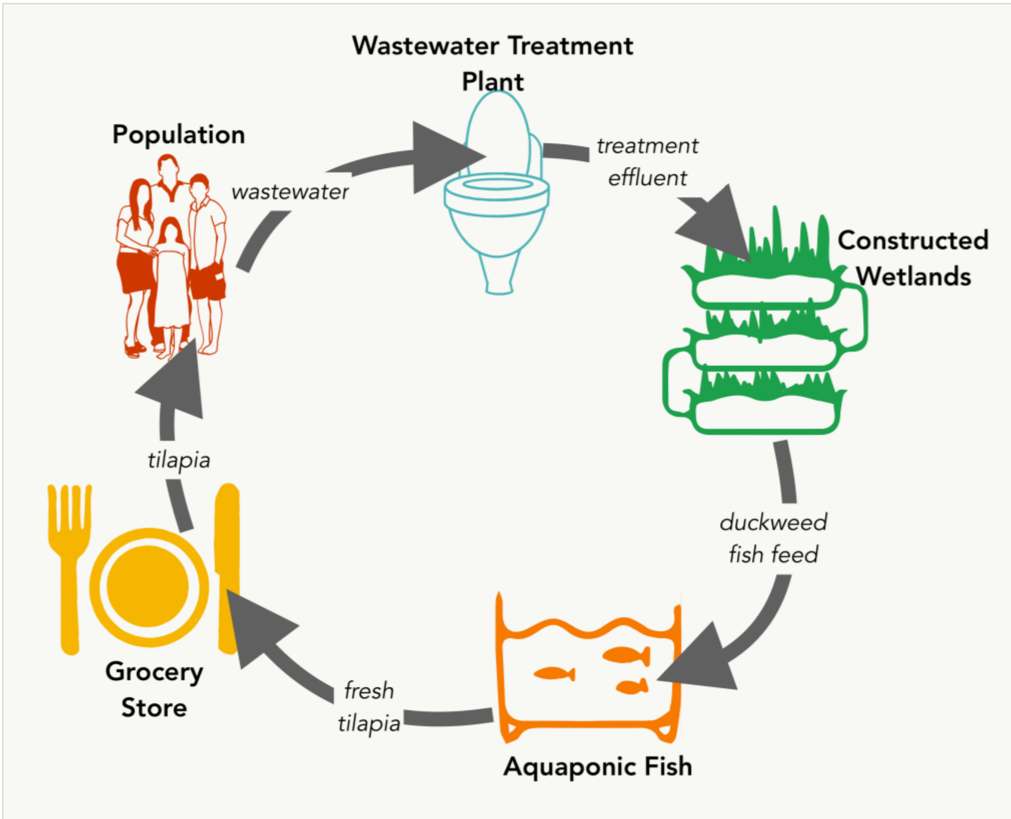


Figure 2: Example cycle created by the Nutrient Optimizing Modules. Nitrogen flows move from a wastewater treatment plant to a constructed wetland. Duckweed grown in the wetland is fed to aquaponic fish, which are then harvested for sale at grocery stores. Fish is then eaten by the population and the cycle continues.

In the NoM network, BSFs replace the municipal solid waste management actor, receiving solid food waste from zone restaurants, groceries, and population actors. BSFs also become the recipient of human biosolids and septage from the wastewater treatment plants and septic system actors at the zone level. Similarly, zone wastewater treatment plant effluent is rerouted from land application and discharge to CWs, where the duckweed absorbs influent nitrogen. APF are then fed this duckweed and the BSF biomass. Finally, the waste from the APF complete the loop by fertilizing the still-growing APP through their nitrogen rich waste. Both fish and plants are then harvested and sent to zone grocery stores, further offsetting imported foods. Waste sludge and crop waste from the CW-BSF-APF-APP cycle are sent to anaerobic digesters to power the aquaponic pumps.

Research Task 2c: Analysis of Case Study

The resulting NoM network from Research Task 2b is then evaluated based on the ENA metrics presented in Section 3.1. Then these network performance results are compared to existing natural ecosystem food web values.

Research Task 2d: Compare All Case Studies

Finally, in Research Task 2d, all five case studies from Experiments 1 and 2 are compared using ecological network performance indicators, degree of centralization, and life cycle impacts of imports and waste streams.

1.2.4 Network Analysis

The structure and flows embedded in each of the network configurations from Experiments 1 and 2 are evaluated using many of the same ENA metrics highlighted in previous ENA studies (Zhang, Yang et al. 2010, Layton 2014, Zhang, Liu et al. 2014, Chen and Chen 2015, Lu, Chen et al. 2015), such as robustness, ascendancy, development capacity, Finn's cycling index (see Section 3.1 for quantitative ENA metric definitions). In addition, several additional metrics are used to benchmark other aspects of the case study networks. These include a few additional network metrics, such as the degree of centralization of the food networks, their relative modularity, and life cycle impact analysis upstream of inputs and downstream of waste as nitrogen streams. These ENA and other metrics are then used as a means of comparing changes imposed on the baseline model.

1.2.5 Thesis Organization

This thesis is organized into 5 additional chapters. First, Chapter 2 provides a review of literature and introduces some of the emerging biotechnologies explored in this thesis. Chapter 3 defines the network metrics used in this study to evaluate ecological network performance and compare levels of network centralization and modularity among the five case studies presented by Experiments 1 and 2. In Chapter 4, the Agri-Network Centralization Experiment (Experiment 1) methodology is outlined, and its results are then discussed. Chapter 5 outlines the Nutrient Optimizing Module Experiment (Experiment 2) and its results, and then the results of both Experiment 1 and Experiment 2 are compared and discussed. Finally, Chapter 6 summarizes conclusions and future work suggested to improve the Nutrient Microgrid and Urban Agriculture.

CHAPTER 2. REVIEW OF LITERATURE AND EMERGING TECHNOLOGIES

Chapter 2 provides a backdrop onto which ecosystem-inspired design and food systems evaluation will be presented. It begins with a brief survey of food system analyses, including material flow analysis, life cycle impact assessments, and network analysis. It then follows by outlining the parallel, linear lens through which both ecological and human systems have historically been viewed. Finally, emerging biotechnologies are introduced as a means of bridging these parallels. These biotechnologies are described from both life cycle engineering and ecological network perspectives, providing context for their later introduction into the Atlanta food web in Chapter 5.

2.1 Conventional Approaches to Sustainable Cities

The sustainability of the urban food system is a complex issue, requiring input from people, industries, and government. Designers of urban infrastructure must consider a host of issues including food safety, population growth, and infrastructure maintenance. At the same time, designers must also consider environmental impacts, material and energy efficiency, reuse and recycling at end-of-life, and impacts of their designs to future generations (Zimmerman 2003). Researchers have applied a number of analytical methods to quantify the characteristics and sustainability of urban systems in their current iteration, including Material Flow Analysis and Life Cycle Assessment (Mitsch and Jørgensen 2003, Gunders 2012). The following sections present some selected case studies in these areas.

2.1.1 Material and Energy Flow Analysis

Mass Flow Analysis (MFA), allows scientists and engineers to quantify the materials and energy into, around, and out of urban system boundaries (Moriguchi and Hashimoto 2016). Some scientists use MFA to compare to natural ecosystems to assess the sustainability of their examined system. Urban water networks have been extensively studied using this MFA methodology, as water is a material that most readily lends itself to flow analysis. For example, in their study of the Danish water system, Pizzol et al. (2013) studied the municipal water flows in Denmark and compared this network to 12 naturally occurring ecosystems. They found that, while the water network is similar to other human systems, it is significantly deficient in functional performance when compared to the natural systems.

Similarly, food flows have become an increasingly popular application of MFA (Forkes 2007, Singh and Bakshi 2013, Treadwell, Clark et al. 2018). Given their immense roles in both agriculture and human nutrition, nitrogen (N), phosphorus (P), carbon (C) are most often at the center focus of such studies. Studies following flows of N, P, and other food mass into, around, and out of urban areas have been compiled for several purposes. For example. in an exhaustive urban material flow analysis of the urban nutrient systems, Cease, Capps et al. (2015) explore the effects of diet and waste management patterns on nitrogen and phosphorus stoichiometry. Their study calls for a focus in the research community on linking food and waste management networks, highlighting the opportunity for nutrient retention in urban areas.

Wielemaker, Weijma et al. (2016) pursues a similar thrust in their exploration of possible linkages between urban agriculture and new sanitation. Their work builds on the Urban Harvest Approach, which was originally developed to quantify urban water resource cycles (Leusbrock, Nanninga et al. 2015). Their work demonstrates that if any combination of several proposed nutrient recycling strategies is implemented, urban areas can become completely self-reliant in phosphorus and that much of the nitrogen requirement for food production could be met simultaneously.

While the studies mentioned above bring us closer to realizing urban self-sufficiency, they do not analyze the spatial requirement for urban food production. Towards these ends, efforts have also been made to map the global potential for food production within the urban boundary (Clinton, Stuhlmacher et al. 2018). Their study underpins the importance of incorporating spatial considerations when evaluating the potential for urban agriculture and localized food production. Their study demonstrates that some urban areas can increased their self-sufficiency with respect to food by making use of rooftops and undeveloped or underutilized spaces and converting them into urban agriculture facilities.

A select number of studies have also surveyed Atlanta's solid waste from this spatial perspective. Quan, Igou et al. (2017) use the occupancy-based accounting method to estimate the volume of Municipal Solid Waste (MSW), estimating the building density and building functions to calculate the occupancy capacities of all types of buildings, and then multiplying these by the occupancy schedules and the MSW generation ratio provided by national and city-wide surveys (Beck and May 2006, Gunders 2012, Quan, Igou et al. 2017).

2.1.2 Life Cycle Assessment

Another approach to sustainable design and analysis is accomplished by tracing a product's inputs and outputs from production through to end of life. This process, known as Life Cycle Assessment (LCA), dates from the 1990s, when the first product studies were made (Goedkoop, Heijungs et al. 2008). An LCA requires the examination of all the associated stages of a product, from upstream material extraction and manufacturing activities disposal scenarios following use. LCAs then quantify the impacts of products and activities with the aim of revealing the environmental burdens of materials, energy, and emissions associated with these products or activities (NL Ministry of Infrastructure and the Environment 2011). The LCA framework, outlined by the International Organization for Standardization (ISO), is one of the premier methodologies for design for life cycle engineering. LCA offers sustainability practitioners to make design and planning decisions based on systematic input-output analysis, and it enables decision makers to evaluate the environmental impacts of products, processes, and materials from the systems level (Bryden and Dhérent 2009).

LCA has also been used extensively to identify hotspots in industrial agriculture (Weber and Matthews 2008, Del Borghi, Gallo et al. 2014) and waste management value chains (Fuchs, Mihelcic et al. 2011, Corominas, Foley et al. 2013, Jeong, Minne et al. 2015). Combined ecological input-output and LCA studies have even attempted to trace N through all sectors of the N cycle (Singh and Bakshi 2013). Studies reveal huge gaps in knowledge and data, leading to potential uncertainty of between 80-211%, which makes sensitivity analysis in such studies problematic. They then call for more high-resolution data, pointing out that this is needed to afford scientists and policy makers the ability to adequately analyze the life cycle impacts of nitrogen management systems.

2.1.3 *Lessons from Conventional Approaches*

Researchers have applied many strategies to evaluate food, energy, and waste flows through the urban landscape. These methods have included Material Flow Analysis (MFA), Life Cycle Assessment (LCA) and other input-output or mass balance approaches. Table 1 provides an overview of the lessons afforded by some of these studies.

Table 1: Lessons from previous studies on sustainable cities.

Flow	Article Title	Significance
N	Nitrogen Ballance for the Central Arizona–Phoenix (CAP) Ecosystem[1]	One of the first studies to trace nitrogen into and out of an urban ecosystem.
P	Dynamic simulation of phosphorus flows through Montreal's food and waste systems[2]	Exhibits potential opportunities for cycling and agri-waste network synthesis.
N, P	Urban nutrient balance for Bangkok[3]	Suggests methods for estimating food and fertilizer flows using aggregated data from FAOSTAT.
N	Nitrogen balance for the urban food metabolism of Toronto, Canada[4]	Evaluates the impact management policies on the recovery and recycling of imported nitrogen.
N, P	Harvest to harvest: Recovering nutrients with New Sanitation systems for reuse in Urban Agriculture[5]	Highlights opportunity for increased nutrient cycling and urban self-sufficiency.
N, P	Consumer-driven nutrient dynamics in urban environments: The stoichiometry of human diets and waste management[6]	Looks at changing nutrient balances and waste management patterns in developed and emerging markets and highlights opportunities for synthesis.
N	Accounting for the Biogeochemical Cycle of Nitrogen in Input-Output Life Cycle Assessment[7]	Presents an integrated ecological and input-output LCA model for N flows in human and natural systems.

[1] (Baker, Hope et al. 2001)
[2] (Treadwell, Clark et al. 2018)
[3] (Færge, Magid et al. 2001)
[4] (Forkes 2007)
[5] (Wielemaker, Weijma et al. 2018)
[6] (Cease, Capps et al. 2015)
[7] (Singh and Bakshi 2013)

Many researchers have explored possible connections between new sanitation strategies and agriculture nutrient demands, but few have pursued a systems-level approach to evaluate the impacts of such connections. The following section introduces a more integrated approach to sustainable systems inspired by ecological networks.

2.2 Systematic: Ecologically-Inspired Network Analysis and Design

Some studies on food sustainability are representative of a problematic tendency in engineering practice towards reductionism has led some to call for a systems-level approach to solving problems (Pandit, Lu et al. 2015). To counter this tendency, many engineers have begun to employ multisector modeling and simulation to design the next generation of material infrastructure. At Georgia Tech, researchers at the Brook Byers Institute for Sustainable Systems and others explore Intersections at the Nexus of Food, Energy, and Water Systems (INFEWS) with the goal of achieving more sustainable, holistic systems design (Beck and May 2006, Weissburg and Yen 2007, Gunders 2012, Pandit, Lu et al. 2015, Quan, Igou et al. 2017). By adopting network theory to describe flows of material and energy through a system, one can circumvent tendencies toward reductionism and evaluate systemic modifications and their impacts on the urban network. One example of this systematic approach is known as Ecological Network Analysis (ENA), first presented in Section 1.1. ENA provides a systems-level approach that makes it particularly useful for sustainable engineering ideation.

2.2.1 Bio-Inspired Design and Industrial Ecology

Ecological Network Analysis, when applied to human systems, is an extension of the Biologically-Inspired Design approach (Weissburg and Yen 2007). It involves a quantification of the complex organization of biological actors into larger networks of interactions. ENA, which originated through synthesis of input-output analysis and network analysis (Fath and Patten 1999), is one such tool that enables ecologists to identify and quantify the behavior, structure, and function of food webs as a whole, using quantifiable metrics.

ENA can be used as preliminary system design tool with the added utility of nature's blueprint. While the benefits of ecologically-inspired design are many, humanity's understanding of biological systems is by no means perfect (Levin and Lubchenco 2008). Ecology is an evolving landscape, and our understanding of ecosystem structure and function is still maturing. To appropriately apply ecological principles towards the design of human food systems, some historical context provides insight into applications and potential pitfalls.

2.2.2 Background: Natural Food Webs

Natural ecosystems have evolved through periods of material and energy shortages to sustainable configurations of species actors, each with their own functional roles in the network (Schidlowski 1988). Organic materials move through functional groups of producers and consumers, and these materials are finally returned to the system through decomposers (Fath and Halnes 2007). Early in the development of trophic dynamic theory, Lindeman (1942) and Hutchinson (1941) developed mathematical abstractions called "progressive efficiencies" to describe the cycling of material and energy within ecosystems (Patten, Higashi et al. 1990). In so doing, they gave rise to a model of understanding that portrays trophic interactions within ecosystems as linear, acyclic chains, where predators consume prey, and energy and matter move up from producer to consumer sequentially.

These natural system configurations are often represented as a pyramid, illustrated in Figure 3 (Fath 2008).

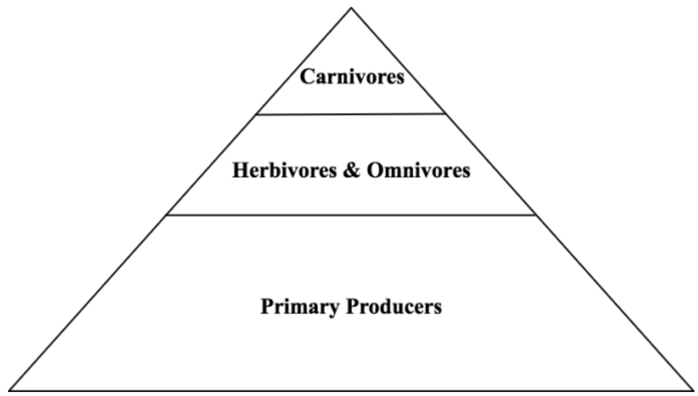


Figure 3: Trophic pyramid and functional role configuration depicting the flow of biomass or energy from primary producers at the bottom up to carnivores at the top, developed prior to inclusion of recycling actors in ecosystem models.

At the base of the pyramid are the primary producers, such as plants, that feed on the energy generated by the sun and nutrients supplied by decomposing organisms, which feed on dead organic matter, or detritus (Mitsch and Jorgensen 2003). Ascending the pyramid, one then encounters primary consumers such as herbivores and omnivores, fed by the producers, and at the top are the carnivore consumers. The movement of energy when one organism consumes another from one trophic level to the next is known as a food chain, and when these chains overlap or intersect, it is termed a food web.

2.2.2.1 Evolving Understanding of Ecological Functional Roles

Although the early models described above enabled ecologists to elucidate some mechanisms underlying observed patterns in nature that arise from the collective behaviors of large groups of organisms (Levin 1992), these models minimized, or even ignored storage of energy and material in successive consumers and the cycling that enables ecosystems to function over successive generations (Patten, Higashi et al. 1990). Recognizing this, Patten et al. (1990) dissected these “acyclic” trophic dynamics, suggesting that an improved view of ecosystem dynamics was needed to more accurately convey the cycling and storage that occur in nature. Further complicating the dialogue, researchers began to recognize the important functional role of decomposers, who take this stored material from dead organic matter and release it in simpler, more bio-available forms for other species to then consume (Mitsch and Jorgensen 2003). Recognizing the absence of this recycling functional group in the literature, multiple researchers have made efforts to review, and in some cases revise existing studies to incorporate detrital actors (Moore, Berlow et al. 2004, Fath and Halnes 2007, Halnes, Fath et al. 2007).

The recycling functional role, consisting of decomposers and detrital feeders named detritivores, is vital to natural ecosystems in that they are nature’s core recycling components (Moore, Berlow et al. 2004). Natural decomposers typically consist of an array of bacteria and fungi that absorb and metabolize up to half of material flows in natural systems, breaking complex tissue into the fundamental components of carbon dioxide, water, and inorganic nutrients that can then be re-introduced into the system (Bergon, Harper et al. 1986, Freedman 1998).

2.2.2.2 Ecological Network Analysis (ENA)

In biology, network indices are used from the macro scale to the micro scale. Scientists use network analysis to study groups or communities of organisms or ecosystems (Finn 1976, Paine 1980, Ulanowicz and Platt 1985), functional properties of biochemical networks (Kim, Bates et al. 2007), metabolic systems within organisms (Gille, Hoffmann et al. 2007), and even cellular structures, signaling, and regulation (Klamt, Saez-Rodriguez et al. 2007) and gene regulatory pathways (Sotiropoulos and Kaznessis 2007).

Researchers sometimes find it helpful to measure an ecosystem's robustness (see Chapter 3 for quantitative definitions). Natural ecosystems, particularly those that are deemed healthy by independent criteria, exhibit a finely-tuned balance between their efficiency and robustness (Ulanowicz 2009, Ulanowicz, Holt et al. 2014). In other words, when materials or energy move from one actor to another within the food web, this flow has a certain probability that it will move to any number of other actors. If an ecosystem is very specialized, matter or energy has only a few pathways by which it can move, which leads to more efficient flow paths, but this can make the system fragile in the face of species loss. By contrast, in an ecosystem in its early stages, many different species compete for the same materials and energy. In these systems, flows display a robust variety of flow paths along which they can move. Through their research, (Ulanowicz, Holt et al. 2014) determined that healthy ecosystems balance efficiency and robustness, making them stable in the face of perturbations.

2.2.2.3 Lessons from Ecology

Through studies of the emerging properties inherent to natural ecosystems, ecologists have learned that natural systems do not waste. The "waste" from one species provides food for others in their ecosystem (Moore, Berlow et al. 2004, Halnes, Fath et al. 2007). By extension, ecosystems are characterized by cycling of material and energy (Fath and Halnes 2007). As mentioned previously, detritivores assist decomposers in the nutrient cycling and conversion process by breaking down lumps of larger organic material, increasing surface area for the molecular-scale decomposers, and their biomass feeds higher trophic level consumers.

Additionally, in the absence of disturbances, mature ecosystems evolve towards specialization, but this can make them brittle to new disturbances (Ulanowicz 2009). Systems that balance efficiency and redundancy are more stable to perturbations (Ulanowicz, Holt et al. 2014). These concepts will be used to benchmark the case studies presented in this study.

2.2.3 The Human Food Web: Application of ENA to Human Systems

When analyzing human systems, an ecological network approach provides insight into network functions and deficiencies (Odum 1969, Layton, Bras et al. 2015, Layton, Bras et al. 2016, Layton, Bras et al. 2016, Bras, Layton et al. 2017). In their recent study, McMichael (2007) explore the human diet and our role in the greater ecological landscape. They suggest that the species has developed a food production system that is so inextricably linked to natural ecosystems, both as providers of resources and destinations for waste products, that we must redefine the "man-vs. nature" paradigm that distinguishes between natural systems and human systems. They suggest that an integrative approach must be taken that unifies ecosystem theory and human system design to move forward in a more holistic fashion. ENA provides such an integrative approach.

Like ecological food webs, the human food system is populated by nodes, or actors, connected by edges that represent flows of material or energy between these actors. Unlike ecological trophic webs, human food system actors inhabit both the biosphere, such as crops or vegetation, livestock, and human consumers, as well as the technosphere, including grocery stores and food processing facilities, wastewater treatment infrastructure, synthetic fertilizer distributors, and transportation mechanisms between these. This section provides an overview of the historical applications of ENA as an analytical tool for human systems.

2.2.3.1 ENA Applications in Industry

Researchers have used ecological network metrics to analyze the performance of industrial systems, finding that they are strongly outperformed by traditional food webs (Layton, Bras, and Weissburg 2015). In two such studies that analyze a carpet network in Atlanta, Georgia, Layton, Bras et al. (2016) demonstrate that certain ecological network indices can be used to reduce costs and emissions. Later, Layton, Bras et al. (2016) demonstrate the effectiveness of implementing a decomposer role (i.e. agriculture) within EIPs and how detritivores can improve efficiencies throughout the industrial network.

Similarly, in his work, Reap (2009) used traditional performance metrics (i.e., cost and emissions) and biomimicry metrics (i.e., linkage density, predator ratio, specialized predator ratio, generalization, vulnerability, cyclicity, Finn's cycling index, and mean path length) to optimize the system with respect to reuse and recycling flows. A full description of these network indices and their mathematical definitions can be found in Section 3.1.

Natural ecosystems grow and evolve towards a sustainable state. External pressures or disturbances often shape this process, as species react to food shortages, environmental changes, or migrations into or out of the ecosystem. This ecological transformation is characterized by an increased ecosystem independence from external resources (Odum 1969). This concept has been applied to human systems to determine the relative sustainability of these systems through Ecological Network Analysis (ENA). By quantifying the interdependence of a system's actors and the organization of flows between them, practitioners can determine the sustainability of human systems (Bodini and Bondavalli 2002). When a system moves towards into a more "mature" state in the absence of disturbances, the actors within it will become more specialized, and the flows will become more organized, thus increasing the metric value called Average Mutual Information (*AMI*).

Kharrazi, Rovenskaya et al. (2013) note that a high level of efficiency can reduce costs and consumption of resources, which, in the case of food production, would likely be more favorable from a material or energy perspective and potentially lead to apparent reduction in the environmental "footprint" of food products' life cycle impact. However, Kharrazi et al. also note that efficiency at the expense of redundancy is most favorable in a system that is unlikely to face disturbance, as these systems are more brittle. Ulanowicz (2009) notes that a successful ecosystem will exhibit a balance of efficiency and redundancy, to enable it to rearrange if faced with shortages or perturbations. This balance characterizes the "window of vitality," pictured in Figure 4.

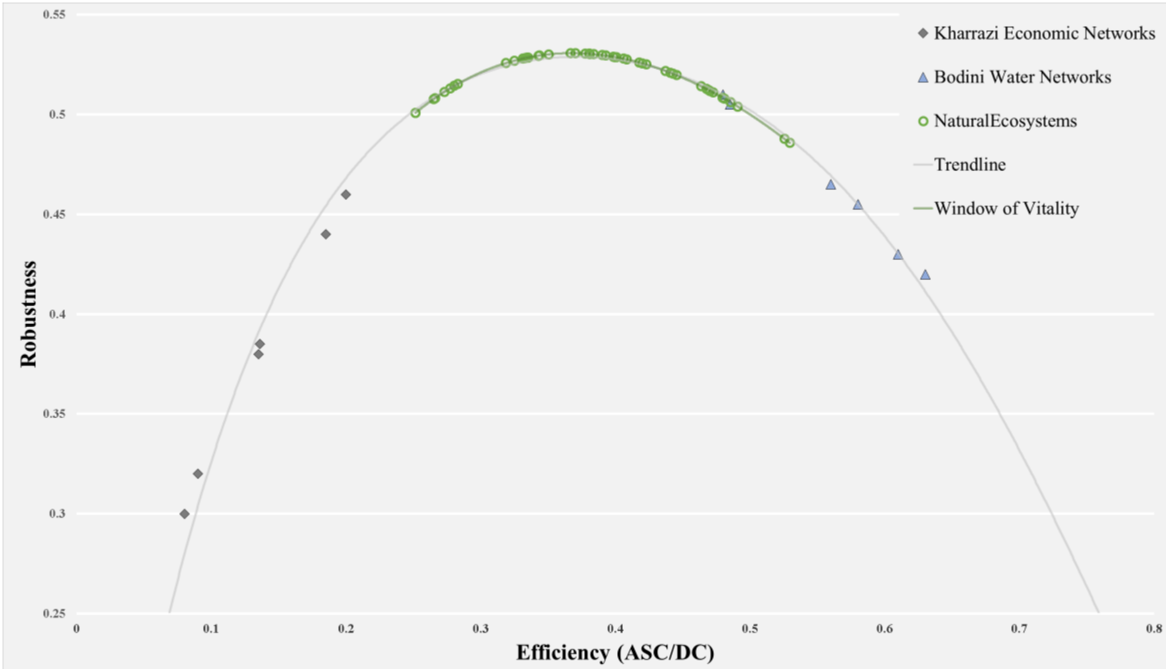


Figure 4: Efficiency vs. Robustness Curve.

Layton, Bras et al. (2015) combined literature characterizing water networks (Bodini, Bondavalli et al. 2012), economic networks (Fath 2015), world zinc network (Graedel, van Beers et al. 2004), and 93 ecosystems and plotted their results onto this window of vitality curve found in Figure 4.

2.2.3.2 ENA Applications in Urban Systems

In addition to industrial systems, ENA has also been used in several case studies to quantify urban networks. Zhang et al. analyzed the urban water network for Beijing and the urban energy networks of four different cities in China (Zhang, Yang, and Fath 2010; Zhang et al. 2010). To analyze the networks' structure and relationships, the authors created different functional groups of actors for each present within the cities. The water network actors included the industrial sector, ecological environment, agricultural sector, rainwater collection system, wastewater regeneration system, and the domestic sector. The energy network had many more actors, but included entities such as oil refinery, construction, and household. Starting from the flows between the different network compartments, the authors could calculate the contributions – or weight – of each actor to the overall network. These weights account for both the direct and indirect flows between the compartments and comparing them to the trophic levels can give information about the structure of the network. Furthering the analysis, the authors used network utility analysis to understand the relationship between the different compartments (Zhang et al. 2010; Zhang, Yang, and Fath 2010). There has been a call to expand the analysis on these urban metabolism networks to include information indices in the metrics of ascendency and development capacity (Chen, Fath, and Chen 2010).

Chen and Chen have used ENA in conjunction with energy flow analysis and input-output analysis to look at the urban energy consumption in Beijing (Chen and Chen 2015). This study used network control analysis, which investigates how actors control one another through their inputs and outputs. Controlled energy is like embodied energy, as it looks at the motivation behind the energy use. For example, the energy consumed by the transport sector is considered the embodied energy of the Transport sector according to IOA, even though it is motivated by the activities in the service sector, because the fossil fuels used end up in the Transport sector (Chen and Chen 2015). However, Chen and Chen concede that these embedded emissions should be attached to the service sector from a network control perspective. Similar forms of the network analysis have been conducted for a natural gas network (Shaikh, Ji, and Fan 2017), carbon metabolism network (Lu et al. 2015), and overall urban food network (Zhang et al. 2014). These uses of ENA with urban systems highlight its potential to analyze large-scale networks.

2.2.3.3 Lessons from Network Analysis of Human Systems

In nature, organisms cycle matter and energy throughout the complex food web, creating a network of interactions. Human systems, by contrast, largely lack decomposers, in effect mimicking the earlier understanding of ecological systems, favoring a "chain" rather than a "web" or "cycle" (Malone, Cohen et al. 2018). Where in nature decomposers convert dead organic matter from all trophic levels into inorganic nutrients that fertilize growth of the producers, human systems often relegate waste into unusable forms in remote locations and use virgin, synthetic nutrient to fertilize food production.

Through their research, Reap, Layton, et al. (2016) demonstrated that Finn's Cycling Index (FCI) serves as a useful measure when compared to traditional objective functions in dictating network improvements to material and energy efficiency when applied industrial networks. For this reason, FCI will be used in this study to evaluate the different network configurations proposed as a proxy to determine the relative material efficiencies of each network where net nitrogen flux is unchanged. It will also be used as an indicator to benchmark the relative material efficiencies of the network once the nutrient optimizing module is introduced.

2.2.4 Additional Network Indices for Ecological and Human Networks

As has been mentioned previously, the emergence of network structures and functions is of interest to the study of ecosystems and ecologically-inspired designers alike, as scientists seek to understand whether and how natural systems abide by organizing rules or principles and whether these principles can inform sustainable design. For example, some research suggests that naturally-occurring trophic networks tend to be fragmented and compartmentalized (Parter, Kashtan et al. 2007, Strona and Veech 2015), while others suggest that decentralization and species diversity provide networks with stability (Waser and Ollerton 2006).

Central to the discussion of sustainable agriculture systems are the questions of decentralization of the food and waste management systems and urban self-sufficiency. In order to evaluate the degree of decentralization appropriate for urban agriculture or urban self-sufficiency enabled by local food networks, one must begin by identifying influential functional actors and sub-networks within a complex network. Next, one can evaluate the strength of connections between sub-groups to then determine the dependence of these sub-groups on the influential actors. To quantify and evaluate these attributes of networks, the concepts of centrality, network centralization can provide useful indicators (Freeman 1978, Dong and Horvath 2007). Centrality identifies and quantifies the influence of individual actors or nodes on a network graph (Freeman 1977).

By better understanding central actors in the food network and the ways in which food networks are compartmentalized or interdependent, engineers and planners can predict and mitigate against disturbances to food supply. They can also compare these metrics against what we have already learned about ecological network properties to better understand food system sustainability from a whole-network perspective. These concepts will be further defined with quantitative metrics in Section 3.2.

2.2.5 Summary of Ecologically-Inspired Network Design and Analysis

The notion that urban material networks can be likened to ecosystems, and by extension that ecological network analysis can aid in the characterization of human systems, has led to ENA's application as an analytical tool in both industrial and urban systems. By characterizing patterns and functional emergence in ecological systems, such as robustness and cycling, we can apply these principles to the design and analysis of human systems and make them more sustainable. Additionally, by understanding the degrees of centralization and modularity of different food system configurations, we can evaluate the network performance resulting from different urban farming configurations and predict the impacts to local sub-networks arising from disturbances to food supply.

2.3 Emerging Biotechnologies for Sustainable Food System

Multiple technologies have emerged that attempt to augment different parts of the food network. Given the increasing rate of urbanization in recent decades, urban agriculture has become an area of interest for scientists evaluating the future of food. Studies explore many of the considerations surrounding urban agriculture, such as stakeholder engagement and policy (Pothukuchi and Kaufman 1999), while others evaluate different proposed technologies for urban food cultivation, such as use of vertical farming (Al-Kodmany 2018), and rooftops (Thomaier, Specht et al. 2015). Some of the leading concerns raised in the discussion of urban agriculture are the questions of space and the availability of resources (Grewal and Grewal 2012). Clinton, Stuhlmacher et al. (2018) evaluate the global potential to cultivate food in cities by estimating the extent of these potential grow spaces using Geographic Information System (GIS) mapping. Still others look to cities as treasure-troves of yet unrealized nutrient resources, calling for a link between urban agriculture and new sanitation technologies (Esrey 2000, Kaufmann, Meyer et al. 2007, Graaff 2010, Poortvliet, Sanders et al. 2017, Wielemaker, Weijma et al. 2018). This section will highlight some of the food production and waste management technologies emerging, both at the lab and field scale.

The idea of a closed-loop human life support system was first introduced by NASA's Ames Research Center in the 1960's, as they began to explore extended missions into outer space (Noordergraaf 2011). They test different configurations and organisms for a completely self-contained, symbiotic life support system to enable deep space explorations. Such closed-loop systems have continued to be of interest in the space exploration field, as researchers examine the integration of decomposers that treat human metabolic byproducts coupled with producers that leverage these recycled products and fix carbon and deliver nutrition to explorers (Blüm 2003). Researchers have extensively tested different combinations and permutations of these for their relative fitness and efficiency (McCoy 2013).

Integrated biotechnologies, or those that combine biological actors into loop-closing modules for nutrient cycling, could assist humans to continue to urbanize more efficiently. Indeed, much of the urban agriculture innovation and technology seen today tends to focus on producer technologies without connecting these to renewable nutrient sources (Simha and Ganesapillai 2017, Al-Kodmany 2018). However, many emerging producer technologies have promising potential connections to recycling, or detrital actors, leveraging waste to provide a more sustainable solution to both food cultivation and waste management (Langergraber and Muellegger 2005, Cease, Capps et al. 2015). CW (constructed wetlands) have been proposed for wastewater treatment as a means to capture phosphorus and N for use as fertilizer (De-Bashan and Bashan 2004) and animal feed (Culley and Epps 1973). When combined with their use as wastewater, organic matter or biosolids treatment mechanisms, insects or aquatic plants grown for livestock feed would elevate the use of CW or BSF (black soldier fly) from waste management actors to true detritivores.

2.3.1 Producer Technologies: Seeding Change

Food must be delivered to inhabitants to support life in cities. As in any ecosystem, producers are required to convert photic energy into chemical energy for use by consumers in the system. Likewise, they adsorb and inert, inorganic molecules, like nitrogen and phosphorus, and convert these into usable building blocks, such as amino acids, that are eventually eaten by consumers and converted into proteins and other cellular structures (Smil 1997). Some of the producers discussed here include hydroponics and Controlled-Environment Agriculture, and aquaponics.

2.3.1.1 Hydroponics and Controlled-Environment Agriculture

Closed systems with controlled, self-contained environments for vegetable and livestock cultivation could help to ease concerns regarding eutrophication and water usage in both agriculture and livestock operations (Touliatos, Dodd et al. 2016, Van Ginkel, Igou et al. 2017). Controlled-Environment Agriculture (CEA) is inherently isolated from neighboring waterways, which reduces eutrophication and water consumption by nearly 90% over conventional agriculture (Van Ginkel, Igou et al. 2017). One example of CEA is hydroponics, which is a type of agriculture that uses a soilless grow medium to cultivate vegetation, can reduce land use by as much as 80% if done using vertical farming methods (Barbosa, Gadelha et al. 2015, Touliatos, Dodd et al. 2016, Van Ginkel, Igou et al. 2017).

2.3.1.2 Aquaponics, Insects, and other Producer Technologies

CEA also facilitates coproduction of symbiotic organisms by bringing parallel and complementary processes in close proximity with a closed, controlled cycling of water and nutrients (Love, Fry et al. 2014, Goddek, Delaide et al. 2015). This symbiosis has been shown to improve overall efficiency of industrial systems (Asmala and Saikku 2010, Bregnballe 2015). One example of this symbiotic CEA practice is aquaponics, or the cultivation of fish and plants together in nutrient recycling system whereby plants leverage fish wastewater as nutrient. Fish benefit the plants by producing a usable nitrogen nutrient source for plants, and without the plants' filtering action, fish would gradually poison themselves with nitrogenous wastes (Thorne, Santos et al. 2013, Hindelang, Gheewala et al. 2014, Goddek, Delaide et al. 2015, Delaide, Delhaye et al. 2017). Aquaponics has been shown to use input nutrient more efficiently when compared to separate, conventional grow systems (Cerozi and Fitzsimmons 2017, Delaide, Delhaye et al. 2017). This stems from the fact that aquaponic plants are grown without the addition of fertilizer, as fish waste water provides all required nitrogen, phosphorus, and potassium. Thus, when combined, fish and plant cultures require only the input of fish feed, energy, and water (Tyson, Treadwell et al. 2011, Trang and Brix 2014).

In addition to exploring human food production alternatives, new technologies have looked to other natural inputs for viable alternatives for livestock nutrition. Researchers have explored duckweed, a highly proteinaceous and starch-rich plant, as a feed alternative for livestock (Hillman and Culley 1978). Black soldier flies (BSF), crickets, and other insects have also been proposed as viable alternatives to other protein sources in animal feed (Charlton, Dickinson et al. 2015, Cohen, Malone et al. 2018). When compared for life cycle impacts to fishmeal and rapeseed, BSF protein has been demonstrated to reduce in the global warming potential of feed when used in place of other fraught protein sources (Rustad and Steen-Olsen 2016).

2.3.2 Decomposers: Another Bug to Fix

Urban infrastructure systems are designed to treat and remove wastes to support healthy urban ecosystems. However, much is not yet known about the scale at which such systems should be implemented to foster sustainable urban ecosystem maintenance (Corominas, Foley et al. 2013, Cunningham and Gharipour 2018). Applying many of the same justifications as the local food enthusiasts, some suggest that a decentralized wastewater treatment system, one where wastes are treated on site or nearby waste sources is more ecologically benign than the centralized systems in place today (Parkinson and Tayler 2003, Jeong, Minne et al. 2015). This section explores some emerging decentralized waste management strategies.

2.3.2.1 Municipal Solid Wastes

Solid organic wastes, which account for 40% of Atlanta's municipal solid waste (MSW) stream (Beck 2005, USEPA 2012), are a commonly cited source of nitrogenous waste that can be treated using biological intervention. Oonincx et al. (2015) attempt to zero in on waste management strategies via use of biological actors in their study of four types of insects' ability to metabolize organic wastes. They focus on feed conversion ratio, nitrogen efficiency, and biomass conversion rate, finding that black soldier flies (BSF) were able to reduce the overall amount of waste fastest with some of the highest nitrogen efficiencies, meaning that they retain nitrogen in their biomass more efficiently and require less time and space for their cultivation (Oonincx, van Broekhoven et al. 2015). BSF have also have high diet plasticity, meaning they can survive on a varied diet, rather than a controlled, heterogeneous diet, which is helpful in the highly heterogeneous urban organic waste stream (Nguyen, Tomberlin et al. 2015).

2.3.2.2 Wastewater Treatment

Biotechnologies assist in the treatment of aqueous wastes via centralized wastewater treatment infrastructure, but the current system paradigm still contributes to eutrophication burdens mentioned in Chapter 1. According to a report published in 2009, 91% of all wastewater facilities in the Atlanta Metropolitan Region presently use advanced secondary and tertiary methods to treat wastewater (AECOM 2009), which means they use microorganisms to convert nitrogen into nitrogen gas and microbial biomass, known as "biosolids," which is easier to later filter than the original aqueous nitrogen (ASCE of Georgia 2014). However, although they leverage costly bioprocesses to remove nitrogen from drinking water, these plants still release much of the nitrogenous effluent and the filtered biosolids back into the surrounding ecosystems, which has resulted in the Chattahoochee's diminished ability to assimilate this nitrogen flux in recent years (Calhoun, Frick et al. 2003, Frick, Zaugg et al. 2003).

When Atlanta's water treatment system was evaluated using LCA, researchers found that the centralized system contributes not only to local eutrophication burdens to the neighboring watershed, as discussed in Section 1.1, but it also adds to the increasing burden to landfills in neighboring communities (Jeong, Minne et al. 2015). Transport and disposal of the solid product of wastewater operations, known as human biosolids, is becoming more expensive for wastewater providers in the Atlanta Metropolitan Region (AECOM 2009). Human biosolids consist of the biological residues produced by microbial biomass during biological processing of wastewater (Beecher, Crawford et al. 2007). The number of landfills that accept biosolids residuals is shrinking, resulting in concerns that future regulatory or waste industry issues will result in the inability to dispose of residuals. High fuel costs make it cost prohibitive for local wastewater providers to transport biosolids residuals to other areas for disposal. Here, too, BSF have the potential to provide additional assistance. They have been shown to thrive on feces and human biosolids, providing additional opportunities for combined waste streams or use in wastewater management, where both organic waste in the form of kitchen-sink food scraps and feces are present (Banks, Gibson et al. 2014).

To address some of the issues surrounding waste management, researchers also have suggested use of aquatic plants for removal of suspended solids and wastes, via macrophytic conversion to biomass in constructed wetlands (CW). Horizontal flow constructed wetlands have been successfully demonstrated for wastewater treatment (Bodin 2013), swine lagoons (Cheng, Landesman et al. 2002), and for treatment of aquaculture effluent (Lin, Jing et al. 2002). One downside cited by researchers to the use of horizontal flow CW in an urban setting is the footprint that it has historically occupied (Cunningham and Gharipour 2018). To address these concerns, advances have been achieved at employing the controlled-environment agriculture (CEA) strategies of recirculation in the form of vertical flow CW (Brix and Arias 2005, Iamchaturapatr, Yi et al. 2007). These systems cover only a fraction of the land requirement of horizontal systems, and, when compared to horizontal flow CW, the vertical flow CW has been shown to more effectively remove total nitrogen from domestic wastewater (Fuchs, Mihelcic et al. 2011). LCAs conducted to compare use of constructed wetlands to conventional wastewater treatment infrastructure have revealed that CWs have diminished environmental impact regarding resource consumption and greenhouse gas emissions over conventional wastewater treatment infrastructure. Even considering the need for energy-intensive recirculation in vertical wetlands, the overall environmental impact is reduced when compared to traditional wastewater treatment. Additionally, both wetland designs were demonstrated to have negligible impacts on respiratory organics, radiation and ozone (Fuchs, Mihelcic et al. 2011)

2.4 Summary of Review and Thesis Context

Studies demonstrate that ecological principles can be used to evaluate and design more sustainable human networks waste (Odum 1969, Reap 2009, Chen, Fath et al. 2010, Layton, Reap et al. 2012, Chen and Chen 2015, Layton, Bras et al. 2015, Layton, Bras et al. 2016). Through their work, scientists have identified functional roles in nature, such as decomposers and recycling actors (Moore, Berlow et al. 2004, Halnes, Fath et al. 2007), that are currently lacking in the human food network (Cohen, Malone et al. 2018, Malone, Cohen et al. 2018, Wielemaker, Weijma et al. 2018). This study applies ENA in the design stage to evaluate potential linkages and functional role additions within the Atlanta region's urban food network with the aim of arriving at a more robust food network configuration. It uses ENA, modularity, and centralization metrics to compare different possible connections between existing nitrogen network actors in the Atlanta Metropolitan Region to better understand how changes to the configuration of nitrogen flow conveyance affects ENA structural and flow attributes. Chapter 3 presents the network metrics leveraged in this study with their quantitative definitions. The following sections evaluate ways in which modifications to the level of centralization of the agriculture and livestock industries change networks' ecological indices (Chapter 4), and then proposes the addition of biotechnology modules to improve network cycling (Chapter 5).

CHAPTER 3. NETWORK ANALYSIS METRICS

Network analysis provides a means to evaluate connectivity and flows between actors in the food production system and introduces opportunities to benchmark these structure and flow indices against naturally-occurring ecosystems. By comparing network metrics to those of natural systems, this study tests how changes to the Atlanta Metropolitan Region's food web affect network performance. The following sections describe the quantitative definitions for the network metrics used in this study. The network metrics outlined in this chapter include Ecological Network Analysis (ENA) structure and flow indices (Section 3.1) in addition to other network metrics, including modularity and centralization (Section 3.2). Centralization is introduced to provide a quantitative basis to compare the case studies presented in the Agri-Network Centralization Experiment, which tests the hypothesis that decentralized food systems are better than more centralized systems. The following sections provide the definitions and equations used to determine network performance for all four case studies in the Agri-Network Centralization Experiment (Chapter 4) and the additional case study in the follow-up experiment, Nutrient Optimizing Module Experiment (Chapter 5). In both experiments, ENA and centralization are determined for each case study, and then centralization indices are then compared against ecological network indices to explore emerging patterns.

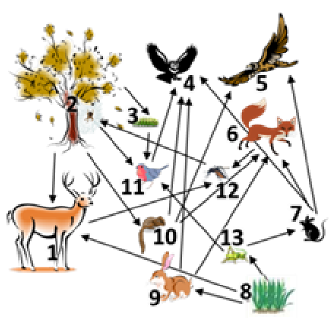
3.1 Ecological Network Analysis

Ecological Network Analysis (ENA) was introduced in Section 1.1.1, and some case studies were then presented in Section 2.2. Definitions of the structure and flow indices and quantitative methods employed by ENA are described below.

3.1.1 Structure Analysis

3.1.1.1 Network Construction: Adjacency Matrix

Network construction is the first step in the calculation of such metrics. This involves the identification of the actors in the network and the connections between them, as in the predator-prey exchanges of material or energy. Figure 5 shows two representations of the same food web, with corresponding species enumerated in the web and matrix representations.



F = (prey × predators)

prey \ predators	1	2	3	4	5	6	7	8	9	10	11	12	13
1	0	0	0	0	0	0	0	0	0	0	0	1	0
2	1	0	1	0	0	0	0	0	0	1	1	0	0
3	0	0	0	0	0	0	0	0	0	0	1	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	1	0
7	0	0	0	1	1	1	0	0	0	0	0	0	0
8	1	0	0	0	0	0	0	0	1	0	0	0	1
9	0	0	0	1	0	1	0	0	0	0	0	0	0
10	0	0	0	1	1	1	0	0	0	0	0	0	0
11	0	0	0	1	0	0	0	0	0	0	0	0	0
12	0	1	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	1	0	0	0	1	0	0

Figure 5: On the left, a hypothetical food web with a number corresponding to the species. Right: the FW matrix representation of the hypothetical food web. Figure adapted from (Layton, Bras et al. 2016).

Above, the structural representation of connections, or links, between actors (left) is shown in an adjacency matrix (right), with columns to represent predators and rows to represent prey (i.e. $f_{ij} = 1$ represents a link between prey (i) and predator (j)). Within each cell, ones denote the presence of a link and zeros are used in the absence of a link.

3.1.1.2 Structure-Based Metrics

Using the adjacency matrix illustrated in Figure 5, the following structure-based metrics can be calculated to quantify certain topological characteristics of food webs.

Number of Species (N): The total number of species in a FW. This term is also commonly denoted as "species richness" and can be represented by the number of rows or columns in a FW matrix (Briand 1983).

Number of Links (L): The number of direct links between species in a FW. This term is represented by the number of nonzero interactions in the FW matrix (Briand 1983).

$$L = \sum_{i=1}^{m} \sum_{j=1}^{n} f_{ij} \tag{1}$$

Linkage Density (L_D): The ratio of the total number of links to the total number of species within a network (Schoener 1989).

$$L_D = {}^{L}/_{N} \tag{2}$$

Prey (n_{prey}): The species which are consumed by at least one other species. This relationship is represented by the number of non-zero rows within a FW matrix (Schoener 1989).

$$f_{row}(i) = \begin{cases} 1\ for\ \sum_{j=1}^{n} f_{ij} > 0 \\ 0\ for\ \sum_{j=1}^{n} f_{ij} = 0 \end{cases} \tag{3}$$

$$n_{prey} = \sum_{i=1}^{m} f_{row}(i)$$

<u>*Predator ($n_{predator}$):*</u> The species which consumes at least one other species. This relationship is represented by the number of nonzero columns in a FW matrix (Schoener 1989).

$$f_{col}(j) = \begin{cases} 1\ for\ \sum_{i=1}^{m} f_{ij} > 0 \\ 0\ for\ \sum_{i=1}^{m} f_{ij} = 0 \end{cases} \tag{4}$$

$$n_{predator} = \sum_{j=1}^{n} f_{col}(j) \tag{5}$$

<u>*Prey to Predator Ratio (P_R):*</u> The ratio of the number of species consumed by another species to the number of species that consume another species.

$$P_R = {}^{n_{prey}}/{}_{n_{predator}} \tag{6}$$

<u>*Generalization (G):*</u> The average number of prey consumed per predator within the FW. This is calculated by the summation of the columns in a FW matrix, and then dividing the number of columns with non-zero elements ($n_{predators}$).

$$G = {}^{L}/_{n_{predator}} \tag{7}$$

<u>Vulnerability (V):</u> The average number of predators per prey in a FW. This is calculated by the summation of the rows in a FW, then dividing by the number of rows with non-zero elements (n_{prey}).

$$V = {}^{L}/_{n_{prey}} \tag{8}$$

<u>Cyclicity (λ_{max}):</u> A measure of the strength and presence of cyclic pathways present within the system. This is calculated by finding the maximum real eigenvalue of the transpose of the FW matrix. The transpose of the FW matrix is A (Allesina, Bondavalli et al. 2005, Fath and Halnes 2007)

$$\lambda_{max} = max, real\ eigenvalue\ solution\ to: 0 = \det(\boldsymbol{A} - \lambda\boldsymbol{I}) \tag{9}$$

<u>Connectance (C):</u> The number of actual direct interactions (L) in a FW divided by the total number of possible interactions (N^2). If one forbids cannibalism, then the number of possible interactions is diminished, resulting in the denominator becoming the fraction of non-zero off-diagonal elements in the FW (Yodzis 1980, Briand 1983, Warren 1990).

$$C = {}^{L}/_{N}\,2 \tag{10}$$

where a_{ij} is the pairwise adjacency or connection strength between nodes *i* and *j* in the adjacency matrix **A** (Dong and Horvath 2007).

Fraction Specialized Predator (P_s): The fraction of predators that are specialized, meaning that they only feed on one type of prey. This is found using the following formulas:

$$f_{col}(j) = \begin{cases} 1\ for\ \sum_{i=1}^{m} f_{ij} > 0 \\ 0\ for\ \sum_{i=1}^{m} f_{ij} = 0 \end{cases} \tag{11}$$

$$n_{s-predator} = \sum_{j=1}^{n} f_{s-col}(j) \tag{12}$$

$$P_s = n_{s-predator} / n_{predator} \tag{13}$$

where n_s is the number of specialized predators, which equals the number of columns in the food web matrix [**F**] that have only one nonzero entry. P_S is then found by dividing the number of specialized predators (n_S) by the number of predators (i.e. the number of columns in [**F**] with non-zero entries).

3.1.2 Flow Analysis

Ecologists may choose to incorporate the magnitudes of flow between network actors in what is known as flow analysis (Finn 1976). The calculation of flow-based metrics requires information regarding both structural and flow characteristics.

3.1.2.1 Network Construction: Flow Matrix

Contrary to the calculations of the structural metrics, flow metric calculations use a $N+3$ x $N+3$ food web flow matrix (Figure 6) that includes inputs from outside the system (row zero), exports to outside the system (column $N+1$), and losses from the system (column $N+2$) Figure 6. A flow from actor i to actor j is represented as a real value by t_{ij}, which is the i^{th} row and j^{th} column entry in this matrix. A value of zero for t_{ij} means no material or energy flow occurs from actor i to j and, thus, no link exists.

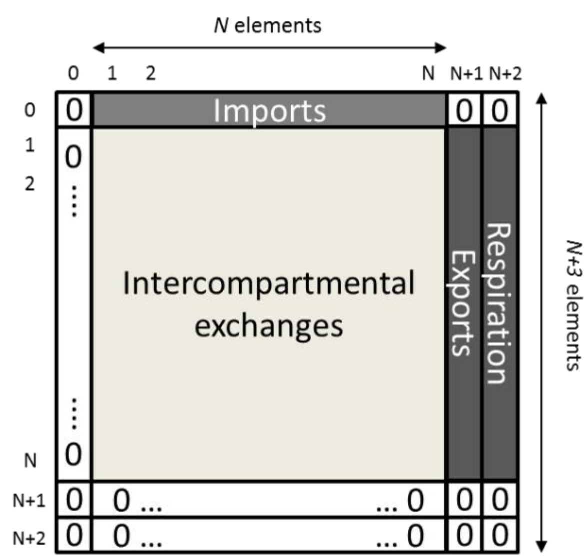


Figure 6: An example of a flow-based matrix [T] (Scotti, Bondavalli et al. 2009).

Using the procedures outlined above, ecologists can then calculate several structure and flow-based metrics, such as Finn's Cycling Index, or the likelihood of materials or energy to return to a compartment once it passes through, robustness, or redundancy of flow paths, and efficiency, to diagnose ecosystem functioning.

3.1.2.2 Flow-Based Metrics

This section defines the flow-based metrics used in ENA to quantify emerging properties of food webs when the magnitudes of flows between actors is included.

<u>*Total System Throughput (TST_P):*</u> The sum of all flow magnitudes in an ecosystem. TST_P is a measure of size or level of total activity of the ecosystem (Ulanowicz 2000, Bodini and Bondavalli 2002, Bodini, Bondavalli et al. 2012).

$$TST_P = \sum_{i=0}^{N+2} \sum_{j=0}^{N+2} t_{ij} \tag{14}$$

<u>*Total System Throughflow (TST):*</u> In a steady-state flow analysis, TST quantifies the total amount of material or energy that passes into and through the system. This is effectively the sum of all internal flows plus the imported flows (Fath and Patten 1999).

$$TST = \sum_{j=0}^{N} t_j + \sum_{i=1}^{N} \sum_{j=1}^{N} t_{ij} \tag{15}$$

<u>*Average Mutual Information (AMI):*</u> The degree of specialization in the system or the amount of constraints on the materials and or energy flow. AMI has been suggested as being indicative for the developmental status, or level of system maturity of an ecosystem (Bodini and Bondavalli 2002)

$$AMI = -k \sum_{i=0}^{N+2} \sum_{j=0}^{N+2} \frac{t_{ij}}{TSTp} \cdot log_2 \left[\frac{t_{ij} \cdot TSTp}{\left(\sum_{j=0}^{N+2} t_{ij}\right)\left(\sum_{i=0}^{N+2} t_{ij}\right)} \right] \tag{16}$$

<u>System Ascendency (ASC):</u> Measures the amount of medium that an ecosystem distributes in an efficient way. Thus, providing a single measurement of growth and

development inherent in the system (Ulanowicz 2000, Bodini and Bondavalli 2002, Bodini, Bondavalli et al. 2012).

$$ASC = AMI \cdot TSTp \tag{17}$$

Development Capacity (DC): The maximum potential that a system has at its disposal to achieve further improvements, and serves as an upper bound for ASC (Ulanowicz 2000, Bodini, Bondavalli et al. 2012).

$$DC = -1 \cdot \sum_{i=0}^{N+2} \left[\left(\sum_{j=0}^{N+2} t_{ij} \right) \cdot log_2 \left(\sum_{j=0}^{N+2} t_{ij} \right) \right] \tag{18}$$

$$DC \geq ASC \geq 0$$

Total System Overhead (TSO): *TSO* pertains to redundant flows in the network and might be an indicator as to the point of optimality between flexibility and efficiency (Ulanowicz 2000, Bodini and Bondavalli 2002, Bodini, Bondavalli et al. 2012)

$$TSO = DC - ASC \tag{19}$$

Finn Cycling Index (FCI): Dimensionless number that accounts for percentage of all fluxes generated by cycling, or the fraction of total activity in the system that is devoted to cycling (Finn 1977, Bodini and Bondavalli 2002).

$$TST_C = \sum_{j=1}^{n} \left(\frac{t_{jj} - 1}{t_{jj}} \right) T_j$$

$$FCI = \frac{TST_C}{TST_P} \tag{20}$$

Mean Path Length (MPL) or Average Path Length (APL): The number of actors "visited" by a material or energy flow (Finn 1977).

$$MPL = {TST_P}\Big/{\sum_{j=0}^{N+2} t_j} \tag{21}$$

Robustness (R): Measures the relationship between *ASC* and *DC*, or the organizational constraints in the system vs redundancy, normalizing the systems "degree of order" (Ulanowicz 2000, Fath 2014).

$$R = -k \left(\frac{ASC}{DC} \right) log_2 \left(\frac{ASC}{DC} \right) \tag{22}$$

3.2 Network Centralization and Connectivity

The following sections describe the quantitative basis for centralization metrics. These indices both require cumbersome calculations when applied to large networks, such as the ones presented in this thesis (n>500). To aid in these computationally expensive calculations, this thesis employs a network analyzer called Cytoscape, which is an open-source platform used largely to analyze large protein interaction networks (Tseng and Jiao 1997, Wang, Li et al. 2011, Doncheva, Assenov et al. 2012, Li, Li et al. 2017).

Centralization is a metric used to determine the overall connectivity of a graph or network and in turn the extent to which the network is controlled by one or a select few actors within the network (Freeman 1978). Centralization is an extension of the centrality metric, which is a node-level metric that identifies the specific nodes in a network that have strong influence over other nodes. Centralization can be calculated using the betweenness centrality, degree centrality, or point centrality measures for a network's nodes. The most common definition of centralization uses the degree centrality, sometimes referred to as node connectivity (Doncheva, Assenov et al. 2012), and this is the metric that is used in this study.

Connectivity (k_x): Connectivity, also known as "degree," indexes the potential of a point, or node for control of its neighbors by counting its opportunities for control. In other words, k_x defines nodes based on how integral they are to movement of flows between other neighboring actors (Freeman 1977) where k_x equals the sum of connections with all other nodes (Freeman 1978).

$$k_x = \sum_{j \neq i} t_{ij}, \tag{23}$$

Network Centralization (C_N): Network centralization is an extension of the concept of centrality extended to the whole network. Using this, the centralization of a graph is calculated as follows:

$$C_N = \frac{\sum_{i=1}^{N} k_x(v_*) - k_x(v_i)}{max \sum_{i=1}^{N} k_x(v_*) - k_x(v_i)} \tag{24}$$

where $k_x(v_i)$ is the connectivity measure of point i and $k_x(v_*)$ is the largest connectivity measure in the network, as defined in Equation 22. The quantity defined by $max \sum_{i=1}^{N} k_x(v_*)$ measures the theoretical maximum connectivity of a point v_* in the network if this point was connected to all other points. It follows that $max \sum_{i=1}^{N} k_x(v_*) - k_x(v_i)$ is the largest possible theoretical sum of differences in the node degree (Freeman 1978, Dong and Horvath 2007).

3.3 Summary of Network Metrics

As has been previously mentioned in Chapters 1 and 2, both ecologists and ecologically-inspired designers alike find network analysis a useful tool. ENA and additional network metrics provide practitioners with a means to understand whether and how natural systems abide by organizing rules or principles and whether these principles can inform sustainable design. For this reason, ENA metrics, connectivity, and centralization will be used to benchmark the relative performance of the case studies explored this thesis.

The metrics presented here are used in the following two experiments as a means of comparing different food production case studies. These metrics are used to evaluate network performance for all four case studies in the Agri-Network Centralization Experiment (Chapter 4) and the additional case study in the follow-up experiment, Nutrient Optimizing Module Experiment (Chapter 5). Centralization is used as a benchmark to quantitatively distinguish between the different case studies in the Agri-Network Centralization Experiment (ACE). In both experiments, the ENA and Centralization metric values are determined for each case study, and then the Centralization indices are then compared against ecological network indices to explore emerging patterns.

CHAPTER 4. EXPERIMENT 1: AGRI-NETWORK CENTRALIZATION EXPERIMENT

This thesis applies an ecologically-inspired systems' approach to evaluate and suggest potential improvements to the Atlanta Metropolitan Region's food network. As described in Chapter 1.2, this is accomplished through two related experiments: 1) The Agri-Network Centralization Experiment (ACE), which tests the hypothesis that decentralized agriculture systems out perform more centralized systems; and 2) The Nutrient Optimizing Module Experiment (Chapter 5), which tests the hypothesis that increased cycling improves network performance.

This chapter outlines the ACE experiment, which constructs a baseline model and compares the ENA metrics to multiple urban agriculture models with varying levels of centralization. Section 4.1 starts this chapter by providing an overview of the systems and the actors in the Atlanta Metropolitan Region network. Section 4.2 then describes the methods used to modify the actors in the baseline model to construct the four decentralized urban farm case studies. Section 4.2.1 goes further to provide a more detailed outline of the actors in the ACE and the nitrogen flow assumptions made in this experiment and Section 4.2.3.1 describes in detail the network construction used for each of the four case studies. Next, the four urban agriculture networks are evaluated against the baseline model for their flow differences and network performance, using metrics outlined in Chapter 3, and the results are presented in Section 4.3 and discussed in Section 4.4. Finally, Section 4.5 summarizes conclusions from this first experiment.

4.1 Agri-Network Centralization Experiment Objectives and Overview

As mentioned in Section 1.1, studies have suggested that local, urban food production could mitigate some of the environmental challenges presented by industrialized agriculture (Pothukuchi and Kaufman 1999, Grewal and Grewal 2012, Thomaier, Specht et al. 2015, Al-Kodmany 2018, Clinton, Stuhlmacher et al. 2018). However, there are no studies that evaluate the degree to which urban agriculture should be localized from a food network perspective. The purpose of the Agri-Network Experiment (ACE) is to apply an ecologically-inspired network approach to tests the hypothesis that "local agriculture is better" by comparing three varying levels of urban agriculture centralization to a scenario in which all food is imported from outside of the region boundary.

4.1.1 Research Questions

This first experiment is designed to answer the following research questions first introduced in Chapter 1:

- How does network performance, as measured by ecological network analysis, differ between systems that import all food and systems where food is sourced from within the system boundary?
- When food is sourced within the system boundary, what level of agri-network centralization produces the most favorable ecological network performance?
- Can a correlation between conventional ENA indices and the degree of food system centralization be established?

4.1.2 Agri-Network Centralization Experiment Tasks and Data Sources

The 4 case studies in the ACE are constructed and analysed using the network performance metrics described in in Chapter 3 using the following research tasks first introduced in Section 1.2.

<u>Task 1a: Determine Actors and Their Associated Nitrogen Flows (Section 4.2.2)</u>

The first step in the ACE is to determine the system boundary and the critical actors in the Atlanta Metropolitan Region food system. Simplifying assumptions are made regarding farm and food flows using data from the United States Department of Agriculture (USDA 2014), literature provided by the Atlanta Metropolitan Water District (AECOM 2009), and commodity distribution studies (US Census Bureau 2007, MWPVL 2008, Lin, Dang et al. 2014). Population food requirements and waste patterns were then calculated to estimate the per capita flows of nitrogen into and out of the population(Rose, Parker et al. 2015), and regional assumptions were used to calculate flows to waste management actors (Decker, Elliott et al. 2000, Beck and May 2006, FAO 2011, USDA 2012, Georgia Department of Natural Resources 2018).

Actors are divided into two categories: constant actors and variable actors. The constant actors are comprised of zone populations, restaurants, and wastewater facilities, municipal solid waste handlers. Variable actors include farm actors, including poultry and produce actors. The assumptions and constants used to determine inputs and outputs to each actor and the nitrogen flows between these actors are outlined in more detail in Section 4.2, and calculated flow tables can be found in Appendix A.

Task 1b: Establish A Baseline Case Study (Sections 4.2.3.1 and 4.2.4)

Connecting actors' direct or computed nitrogen flows from Task 1a, a simplified model of the existing network is constructed in which all food is imported and all agriculture products are exported.

Task 1c: Urban farm scenarios (Sections 4.2.3.1 and 4.2.4)

Using the nitrogen flows of food and waste from Task 1a, an urban farm scenario is imagined where food grown in the system boundary is used to meet the food demand within the region. Total imports of food to the system are offset by the products cultivated in the region's farms.

Using the modified assumption that food grown within the boundary feeds the population, 3 Urban farm scenario case studies are constructed using existing productivity, nitrogen input requirements, and waste from the baseline, aggregating the farms from the baseline into increasingly centralized urban farms.

Task 1d: Analysis of Case Studies

Following the completion of these 4 research tasks, the following steps are taken:

1. Analyze all 4 case studies using indicators outlined in in Chapter 3.
2. Compare network performance of each to existing natural food webs.
3. Compare relative environmental impact of imports and waste.

4.2 Materials and Methods

The following subsections introduce the geographic area and system boundary used in this study along with guiding assumptions regarding general flow of materials in the Atlanta Metropolitan Region, outline the important actors in the Atlanta food system, and presents a brief overview of the 4 case studies in the Agri-Network Centralization Experiment.

4.2.1 Overview of Study and System Boundary

This study is situated in the Atlanta Metropolitan Region, located in the state of Georgia, United States of America (Figure 7). The Atlanta Region is selected because the surrounding region is well-seated for the introduction of systems-level integration and restructuring of its food and waste networks. This is due to its unique collocation of industry, urban activity, and agricultural productivity, combined with its sprawling topology.

Figure 7: Map of the State of Georgia with the Atlanta Metropolitan Region system boundary and associated counties. Original image, adapted from (AECOM 2009, Carl Vinson Institute of Government 2018).

Figure 8 shows the 15 counties included in the Atlanta Metropolitan Region alongside the color-coded receiving water basins used in this study.

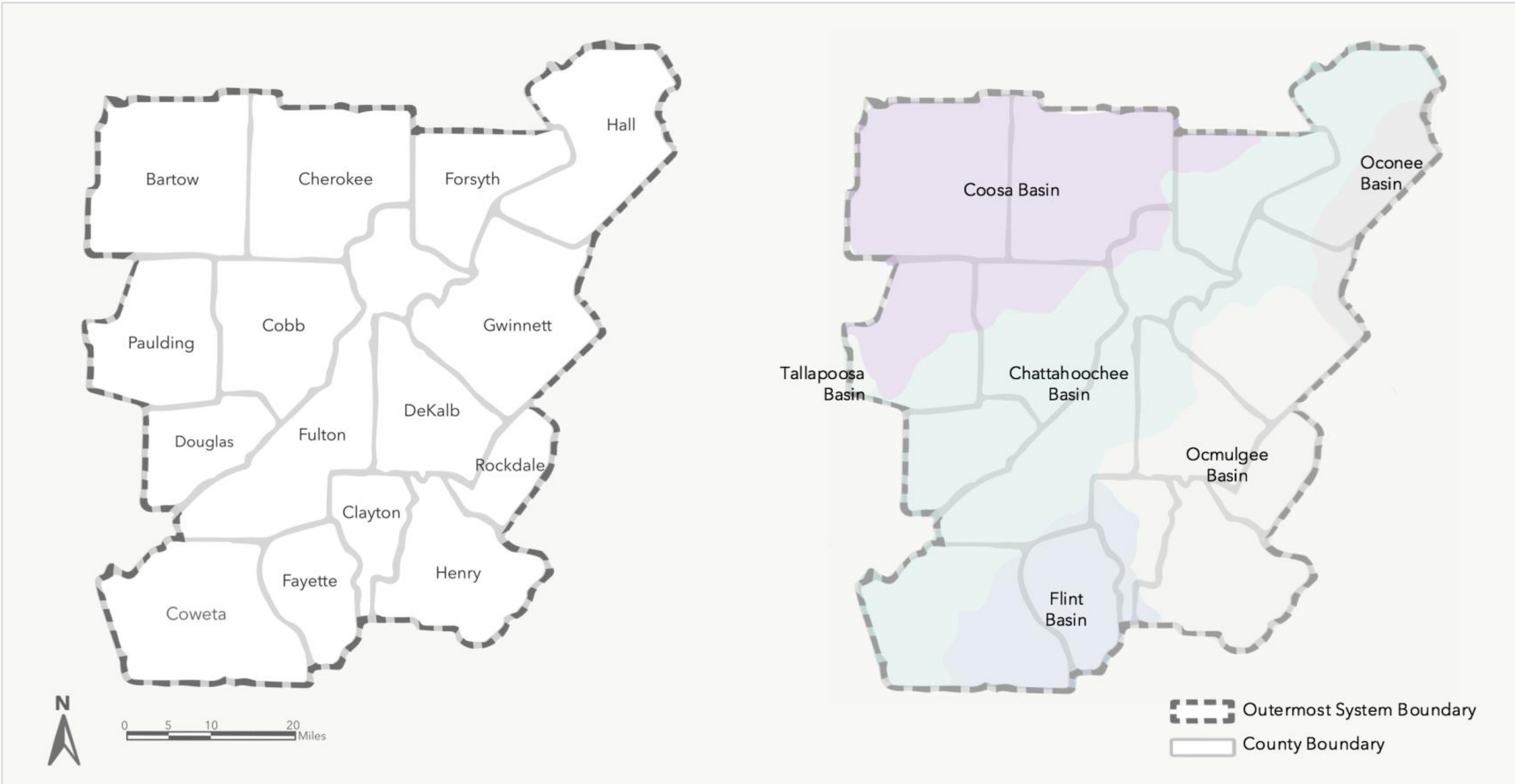


Figure 8: Atlanta Metropolitan Region of study and its included 15 counties (left) and receiving water basins (right). Colors represent different receiving water basins. Original image, adapted from (AECOM 2009).

In Figure 8 one can see the six receiving water basins, represented by different colors. Purple represents the Coosa Basin, light blue is the Chattahoochee, light grey is Ocmulgee, dark grey is Oconee, and the small white portion denotes the Tallapoosa Basin. Chattahoochee receives the majority (53-67%) of regional wastewater effluent, with 42 municipal treatment plants in Fulton, Douglas, Cobb, Forsyth, DeKalb, Coweta, Gwinnett, Paulding, and Hall County effluents. The next largest receivers are Ocmulgee and Coosa, together receiving over 40% of effluents (from Gwinnett, Rockdale, Henry, Clayton, DeKalb, Bartow, Paulding, Cobb, Cherokee, and Forsyth Counties). The basins that receive the least effluent are Flint (4.5%) and Tallapoosa (0.4%). Oconee receives no municipal wastewater effluent from the Atlanta Metropolitan Region.

4.2.1.1 <u>Atlanta Metropolitan Region Assumptions</u>

As previously stated, the first step in Task 1a is to use industry-level data to establish a set of actors in the baseline. The available data used to characterize the nitrogen flows to and from each of these actors was provided in the literature in varying degrees of resolution. Farm inputs, acreage, and productivity as well as population demographics were reported on a county level (Atlanta Regional Commission Research 2010, USDA 2014). Meanwhile, consumption and waste patterns were reported on a per-capita basis (USDA 2012, Cease, Capps et al. 2015, Rose, Parker et al. 2015).

Figure 9 shows the region-county-zone hierarchy used in the 4 ACE scenarios, which is accompanied by an explanation of the procedure used to determine the zones.

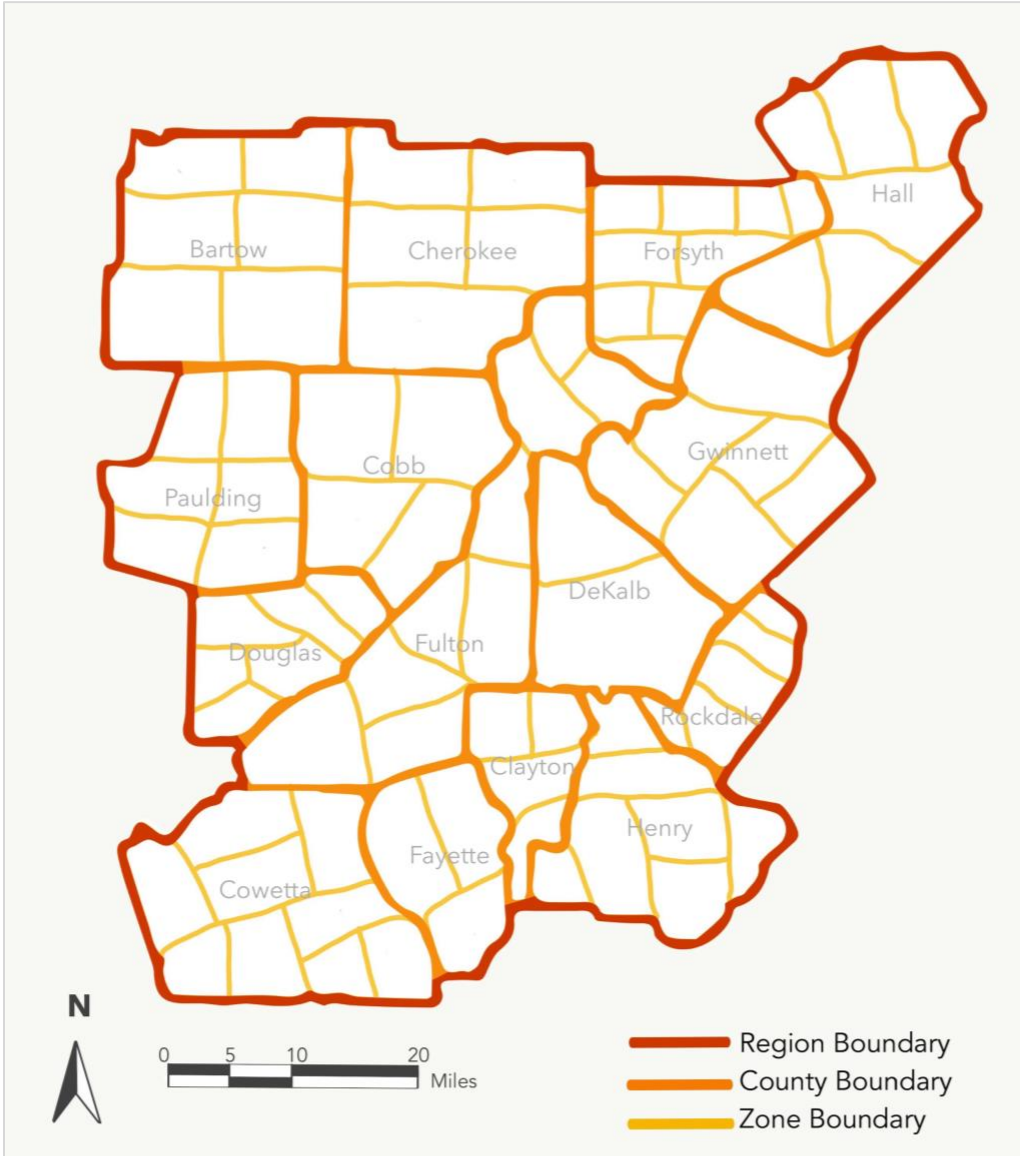


Figure 9: Visualization of geographic area demarcations for all case studies. The region boundary (red) and all 15 counties (outlined in orange) are depicted according to their geographic location. Zones (outlined in yellow) are presented as a visual representation of the water treatment zones.

Zones represented in Figure 9 are derived from the percent of county wastewater treatment capacity managed by a given wastewater treatment plant. The procedure used to determine the zonal nitrogen flows is outlined below:

1. Counties are divided into zone according to the number and relative treatment capacities of wastewater treatment facilities in each county.
    a. Population in each zone is assumed to be proportional to the percent of the county's treatment capacity serviced by a corresponding wastewater treatment facility (see Equation 25).
    b. Farmland, including both poultry and cropland, is assumed to inversely correlate to population density (see Equation 26)
2. Resulting farm productivity, food requirements, and waste flows for each zone are calculated based on the county totals multiplied by the population weighting factor and farmland weighting factor calculated for each zone (see section 4.2.3).

As mentioned in (1a) above, it is assumed that wastewater facilities manage the wastes proportional to their flow capacity, and thus facilities' proportion of county treatment capacities (PCC) are thus treated as population density indicators. A population density weighting factor (PWF) is derived using the proportion of county total flow treated by each facility to establish a zone-level population served, which can be seen in Equation 26.

The population weighting factor (PWF) for zone *i* is calculated as follows:

$$PWF_{i \in j} = \frac{PFC_i}{PCC_j} \tag{25}$$

where PCC_j is the total permitted treatment capacity for county *j* and PFC_i is the permitted treatment capacity for the facility in zone *i* in county *j*. This was then used to find zonal populations for the zone serviced by a given treatment facility by multiplying it by a given county's population, which was found in publicly-available census records (Atlanta Regional Commission Research 2010). Table 2 serves as an example of this breakdown for the zones established within Fulton County. The table shows wastewater treatment facilities and their capacities and associated zones ID's along with the zone population served by each of these facilities.

Table 2: Fulton County zonal wastewater treatment compartments. Population totals for each zone equal the proportion of county flow capacity serviced by the zonal wastewater treatment facility multiplied by the total county population.

Zone/ County ID. No.	Wastewater Treatment Plant Name[1]	2016 Permitted Treatment Capacity (MGD)[1]	Proportion of County Total Flow (%)	Zone Population (No.)[2]	Zone Population Under 20 (No.)[2]
58	Fulton Johns Creek	15	5.83	53,710	14419
59	Fulton Big Creek	24	9.33	85,935	23071
60	Fulton Little Bear Creek	0.1	0.04	358	96
61	Fulton Cauley Creek	5	1.94	17,903	4806
62	Fulton Little River	1	0.39	3,581	961
63	Fulton Camp Creek	24	9.33	85,935	23071
64	Atlanta RM Clayton	100	38.90	358,063	96127
65	Atlanta Utoy Creek	40	15.56	143,225	38451
66	Atlanta South River	48	18.67	171,870	46141
67	**Fulton Total:**	**257.1**	**100**	**920,580**	**247143**

[1] (AECOM 2009)
[2] (Atlanta Regional Commission Research 2010)

In the same way that the population data was only available at the county level, so too was poultry and produce data (as mentioned in 1b above). Using the population density weighting factor developed to determine zone populations, a farmland weighting factor (FWF) is also derived. This FWF assumes that population density and farmland acreage are inversely correlates. Thus, an inverse weighting factor based on the population density function reflects this relationship:

$$FWF_i = \frac{1}{\mathrm{PWF}_i} \times \sum_{i}^{j} \frac{1}{\mathrm{PWF}_i} \tag{26}$$

where PWF_i is the population weighting factor calculated using Equation 27 in a given zone i in county j, and $\sum_{i}^{j} \frac{1}{\mathrm{PWF}_i}$ is the sum of the inverses of the population weighting factors of each of the zones in a given county j. Calculated flow values for population, cropland, and poultry actors can be found in Appendix A.

4.2.1.2 Actors and Flows

This section introduces the general actors used in all of the 4 ACE case studies. These actors are introduced to provide context for their introduction in the case studies that follow. This study focusses on the following industries: poultry and poultry feed industries, fertilizer and produce industries, food distribution, and municipal solids management. Each actor is evaluated for its nitrogen inputs, nitrogen use efficiency (percent of consumed nitrogen that is converted into biomass), and waste products. The generalized schematic used in the actor definition step is pictured in Figure 10.

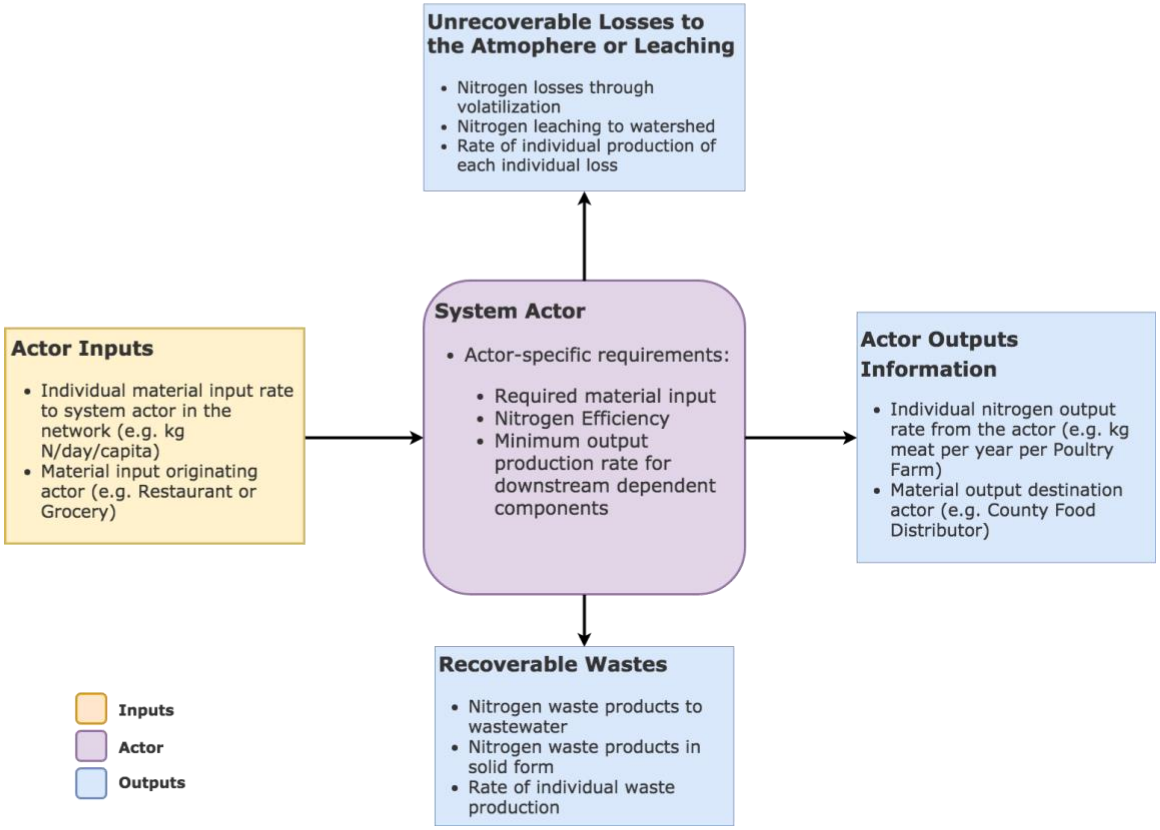


Figure 10: Actor definition schematic.

The actors defined in the Agri-Network Centralization Experiment (ACE) include poultry and produce industry actors, food distribution industry actors, population and restaurant actors, solid and liquid waste management actors, and the 6 water basins in the Atlanta Metropolitan Region. Figure 11 introduces a general schematic for these actors in all 4 ACE case studies. Flows are numbered and described for each of the 4 case studies.

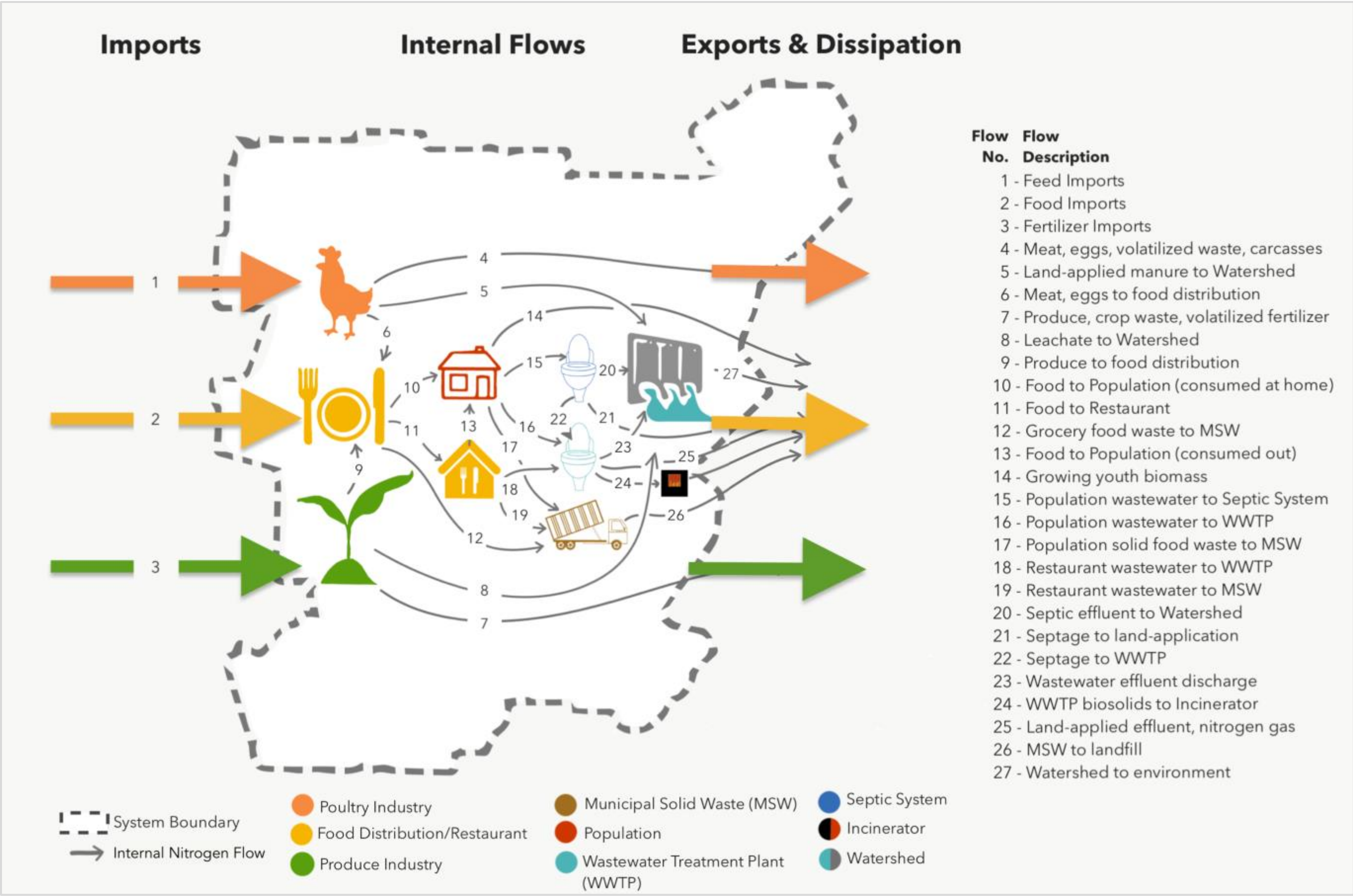


Figure 11: General overview of actors and flows in the Atlanta Metropolitan Region food system. Poultry, Produce and Food Distribution industries are simplified here (orange, green, and yellow icons, respectively). These industries and their connections are the only actors and flows that vary between the 4 Agri-Network Centralization Experiment (ACE) case studies (see 4.2.3).

Flows numbered 10-27 concern movement of produced goods and their associated waste streams, which remain constant in all of the 4 case studies. As can be seen in the schematic, food moves from the food industry to households (flow 10) or restaurants (flow 11) based on reported percentage of meals eaten out (flow 13) (USDA 2012). Food waste that is put in sink food processors (Lundie and Peters 2005) is transferred, along with urine, feces, and sweat, to the zone septic (flow 15) system or wastewater treatment facilities (flow 16), according to the reported percentages of homes with septic service (AECOM 2009). Food waste processed in restaurants from sink food disposal is sent to wastewater treatment facilities (flow 18), while the remaining restaurant food waste is conveyed to municipal solid waste facilities (flow 19). Spoiled or unsold solid food from groceries (flow 12) and households (flow 17) are transferred to municipal solid waste facilities (Gunders 2012). Effluent nitrogen from septic systems (flow 20) is released to the receiving water basin and septic solids (septage) are either applied to land (21) or sent to wastewater treatment facilities (flow 22) (ASCE of Georgia 2014). The majority of nitrogen found in wastewater is either released to the atmosphere through biological processing in wastewater treatment plants or applied to land as effluent or biosolids (flow 25), while some is filtered out by microorganisms and either sent to an incinerator (flow 24) (AECOM 2009, Van Drecht, Bouwman et al. 2009). Any remaining aqueous nitrogen from wastewater treatment is discharged as effluent to the watershed downstream of drinking water sources (flow 23).

The remaining connections in the schematic pictured in Figure 10 (flows 1-9) represent generalized flows amongst the variable actors in the ACE. While these generalized industry-level flows are present in all case studies, the flows within the poultry and produce industries and their connections to food distribution and basin actors change between the 4 case studies evaluated in the Agri-Network Centralization Experiment (ACE). These variable actors and flows are summarized in the following section.

4.2.1.3 Overview of Case Study Similarities and Differences

The different case studies are characterized by varying degrees of agri-network centralization, but many of the network actors are present in every case study. Zone-level actors present in all case studies include wastewater treatment facilities and their incinerators, septic systems, restaurants, and population. County-level actors in all cases include food distributors and municipal solid waste management actors. Finally, region-level food distributors are present in all case studies. The actors present in each scenario are outlined in Table 3, along with their location levels (zone, county, or region). Variations in the degree of centralization of farm flows are summarized in Figure 12, which is followed by an overview of the differences and similarities between the 4 case studies.

Table 3: Actors present in the Agri-Network Centralization Experiment case studies by hierarchical level. Descriptions of each scenario are presented in the section below.

Case Study (no.)	(1) Import/Export Case			(2) Zone Urban Farm Case			(3) County Urban Farm Case			(4) Region Urban Farm Case		
Geographic Hierarchy Level / **Actor**	**Regional Level**	**County Level**	**Zone Level**	**Regional Level**	**County Level**	**Zone Level**	**Regional Level**	**County Level**	**Zone Level**	**Regional Level**	**County Level**	**Zone Level**
*Fertilizer Distribution**	✓	✓		✓	✓		✓					
*Feed Distribution**	✓	✓		✓	✓		✓					
Food Distribution/ Grocery	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
*Produce Farm**			✓			✓		✓		✓		
*Poultry Farm**			✓			✓		✓		✓		
Restaurant			✓			✓			✓			✓
Population			✓			✓			✓			✓
Wastewater Treatment Plant			✓			✓			✓			✓
Septic System			✓			✓			✓			✓
Incinerator			✓			✓			✓			✓
Municipal Solid Waste		✓			✓			✓			✓	
*Poultry Product Distributor**	✓	✓		✓	✓		✓					
*Produce Product Distributor**	✓	✓		✓	✓		✓					

****Denotes that actor presence varies between case studies***

Figure 12 presents a simplified representation, using only produce (cropland) actors, that illustrates the most important differences between the 4 scenarios.

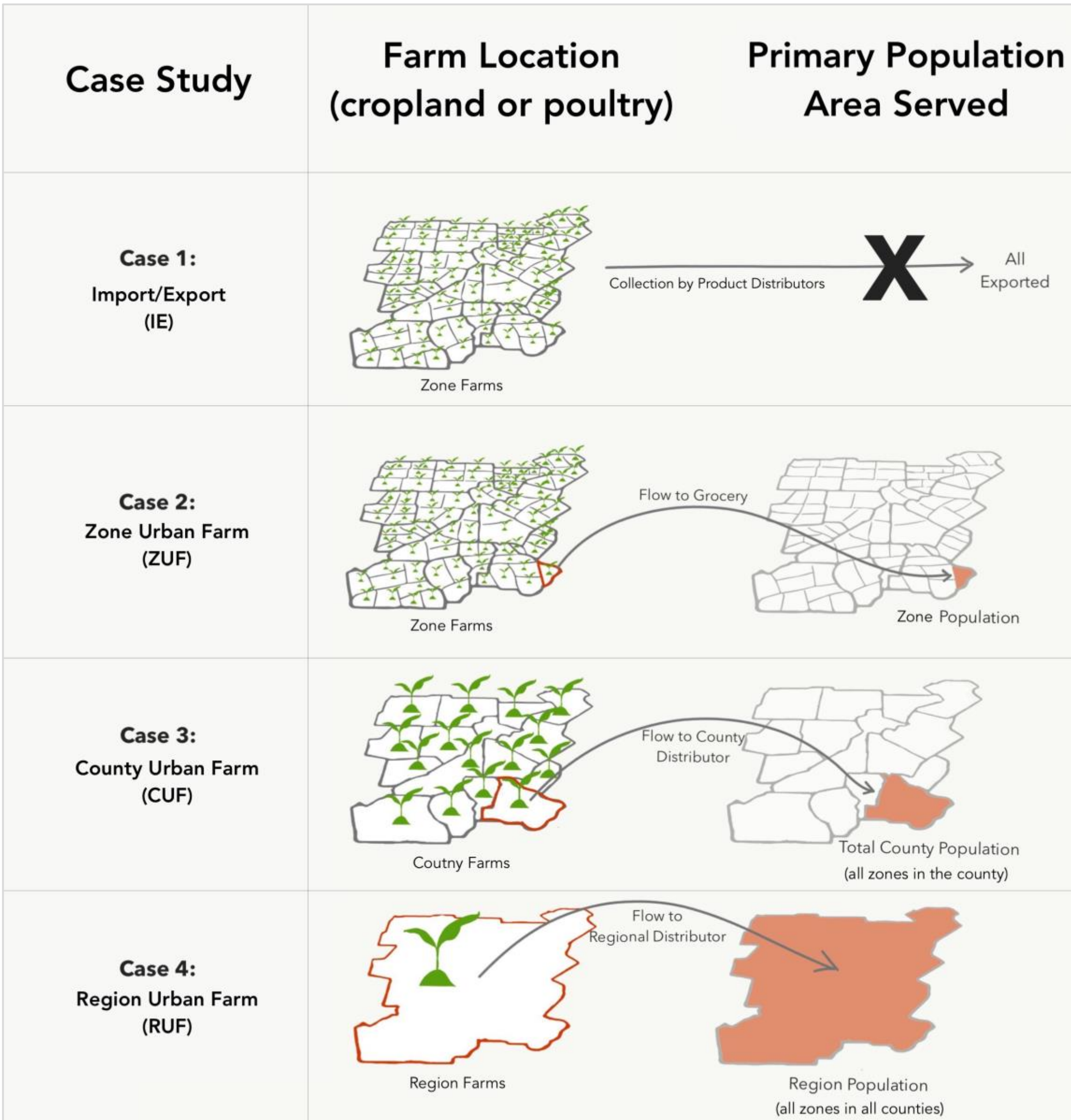


Figure 12: Variable farm locations, corresponding population areas served, and pathways from farm import to zone grocery for all 4 ACE case studies.

This representation highlights the increasing size of the population areas served by farmland actors, from the Import/Export Case, which provides farm products to none of the population, to the Zone Urban Farm Case, which serves mostly the population within a given zone, to the County Urban Farm Case, which primarily serves the county, to the Region Urban Farm Case, which provides food to the whole region. The differences in food flows and connectivity between the 4 ACE case studies is outlined in greater depth in Sections 4.2.3 and 4.2.4.

Building on the actors and their location in the geographic hierarchy described in Table 3 and Figure 12, the following section provides an explanation of the zone-county-region hierarchy assumptions used in the 4 case studies in the ACE and summarizes the differences and similarities between these networks:

1. Baseline network:
    a. Case 1: "Import/Export Case" (IE)
        i. All fertilizer is imported to a regional chemical distributor, then taken by a county-level fertilizer distribution actor to zone-level poultry farms within that county.
        ii. All crop and poultry products are collected from zone farms by county-level produce and poultry product distributors, followed by region produce and poultry product distributors, and finally these products are exported out of the region.
        iii. Poultry waste products are either conveyed to the watershed by runoff, to the atmosphere through volatilization, or disposed.
        iv. All food required in the regional area by the population is first imported to a regional food distributor and then distributed by a

county-level grocery logistics actor to the zone-level groceries within each county.

2. Urban farm Cases:
    a. Case 2: “Zone Urban Farm Case” (ZUF)
        i. All fertilizer and feed are imported to regional chemical and feed distributors, then sent down to a county chemical or feed distributor, and finally to zone-level farmland or poultry actor. (Input feed and fertilizer magnitudes remain the same as in IE.)
        ii. All crop and poultry products are sold directly from the zone-level farms to zone-level grocery stores until the grocery needs of a zone is met. (Total inputs and outputs to zone grocery remain unchanged – only source changes.)
        iii. Poultry or produce products in excess of zone needs are sent up from zones to a county distributor that sells products to the county food distributor, who then sells to all zones within the county until the zones within that county are fed.
        iv. Any additional poultry or produce products, in excess of the county’s need, are then sent up to the regional produce or poultry product distributor, who then sell to the regional food distributor until all food requirements within a region are met.
        v. Any remaining food required within the region is imported from outside the Atlanta Metropolitan Region and sent down the

hierarchy up until the county and then zone area needs are completely met.

b. Case 3: "County Urban Farm Case" (CUF)

   i. All fertilizer and feed are imported to regional chemical or feed distributor, then sent down to a county-level cropland or poultry farm. (Input feed and fertilizer magnitudes remain the same in all cases.)

   ii. All crop and poultry products are sold directly from the county-level farms to zone grocery stores up until the zone needs are met. (Total inputs and outputs to county food distributor remain unchanged – only source changes.)

   iii. Any additional poultry or produce products, in excess of the county's need, are then sold up to the regional produce or poultry product distributor, who then sell to the regional food distributor up until all county food requirements are met.

   iv. Any remaining food required within the region in addition to that which is provided by farms is imported and sent down the hierarchy up until the county and then zone needs are completely met.

c. Case 4: "Region Urban Farm Case" (RUF)

   i. All fertilizer and feed are imported to region-level cropland or poultry farm actor. (Input feed and fertilizer magnitudes remain the same in all cases.)

ii. All crop and poultry products are sold directly from the region-level farms to region-level food distributors up until the regional food need is met. (Total inputs and outputs to regional food distributor remain unchanged – only source changes.)

iii. Any remaining food required within the region is imported to the regional food distributor and sent down the hierarchy to the county food distributor and then zone groceries, up until all zone needs are completely met.

The following sections provide details used to determine constant and variable actors in the 4 case studies.

4.2.2 Constant Actors and Associated Nitrogen Flows (Task 1a)

The following sections outline the actors that remain constant in all of the ACE case studies. These constants include population, restaurant, waste management, and wastewater actors and their associated flows.

4.2.2.1 <u>Population and Restaurant Actors: Assumptions and Constants</u>

Food flows in all 4 models are set by the baseline food requirements of the population, and differ only in their origin, imported in Import/Export Case and from the farms in the 3 Urban farm Scenarios. Assumptions and considerations used to determine flows to zone population and zone restaurant actors are outlined below.

1. <u>Population Actors</u>:

a. County-level populations are divided into wastewater treatment "zones" based on the assumption that wastewater treatment capacity is proportional to population served using a population weighting factor (see equation 25 in Section 4.2.1.1 on page 6967)
    i. The wastewater treatment facilities in each county are assumed to service a portion of the county's population based on the treatment capacity of each of these facilities.
    ii. Zone population sizes are determined according to proportion of the counties' total wastewater treatment capacity.
    iii. The resulting "zone population" actors represent the highest level of resolution for residents in the Atlanta Metropolitan Region.
b. Population actors purchase food from both restaurant or grocery actors in all 4 case studies.
c. Food flows to zonal population actors is the sum of all consumption plus waste, and the value of flow to each population actor remains the same in every case study.
d. Food consumption per capita is calculated based on several guiding assumptions:
    i. All population actors are assumed to consume the same amount of nitrogen per day (±5%) (Cease, Capps et al. 2015).
    ii. Estimated consumption is assumed to be 13.72 g N per day based on adult waste characterization and per-capita consumption studies as follows:

1. Estimated per-capita nitrogen consumption proportions for omnivores versus vegetarians are drawn from literature (1.18 for omnivores to 1 for vegetarians) (USDA 2012).
2. A proportion of vegetarians (3.2%) is assumed based on nationally-reported averages (Vegetarian Times Editors 2008).
3. Adults are assumed to be in nitrogen equilibrium, meaning all consumed nitrogen is evacuated (2.8 g N per day) or excreted (via urine or sweat – 10.98 g N per day) to wastewater (Cease, Capps et al. 2015, Rose, Parker et al. 2015).
4. Youth are assumed to retain 0.7% of consumed nitrogen in their growing tissue (Cease, Capps et al. 2015), reducing their urine contribution to 10.82 g N per day.

e. Food Waste assumptions per capita (e.g. uneaten food scraps, food preparation biproducts, etc.)

   The rate of residential food wasting (20.9% of purchased food) is based on per-capita food waste averages (FAO 2011, Gunders 2012, USEPA 2012).

   i. Wastewater: 2.3% of food waste is assumed to be processed via kitchen sink food waste processor (Lundie and Peters 2005).

   ii. Municipal Solids: 97.7% of food waste is assumed to be sent to the county's municipal solid waste collection (USEPA 2012).

f. Human Waste

i. Urine: it is assumed that the average adult omnivore excretes 10.98 grams of nitrogen each day (Rose, Parker et al. 2015).

ii. Feces: the average adult omnivore evacuates 2.8 grams of nitrogen per day (Rose, Parker et al. 2015).

iii. Using Correcting for 3.2% vegetarian, total urine and feces nitrogen composition is calculated (Cease, Capps et al. 2015) (Vegetarian Times Editors 2008).

iv. All human waste nitrogen is assumed to be evacuated or excreted at home (Rose, Parker et al. 2015).

A summary of the flows to and from population actors can be observed in Figure 13 below.

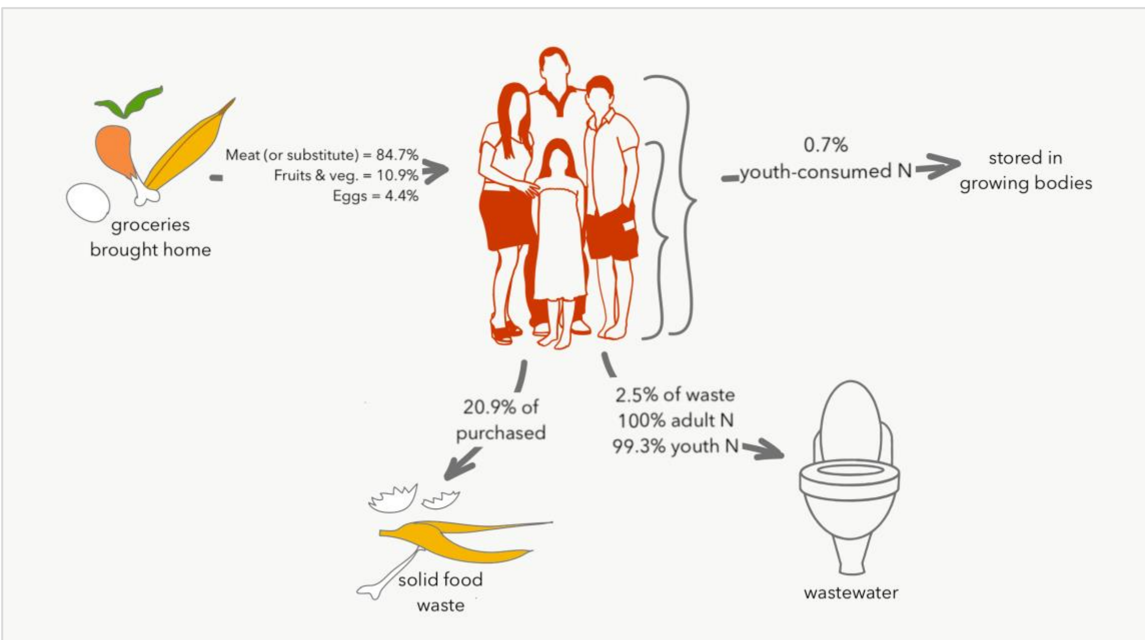


Figure 13: Population actor food and waste nitrogen inputs and outputs.

The flow assumptions and constants listed from the population actors can be found summarized in Table 4 along with a list of variables calculated in this study.

Table 4: Summary of Population and Restaurant assumptions, constants, and values calculated.

Assumption or Calculation	Value	Unit
Per capita food nitrogen consumption rate[1,3,4]	13.72	g N day^{-1}
Fraction of food N assimilated by a child[1,2]	0.7	%
Fraction of food N assimilated by an adult[1]	0	%
Fraction of food wasted at residence or restaurant[6]	20.9	%
Fraction of food wasted by grocery[6]	9.8	%
Fraction of food eaten at restaurants (eaten out) [7]	32	%
Fraction of food consumed at residence (eaten in) [7]	68	%
Fraction of households with kitchen grinder[5]	2.3	%
Total population in zone compartment	varied	number
Total youth population in zone compartment	varied	number
Total population N from urine to wastewater	calculated	kg N day^{-1}
Total population N from feces to wastewater	calculated	kg N day^{-1}
Food waste rate per capita	calculated	g N day^{-1}
Total food consumed (out + in)	calculated	kg N day^{-1}
Total food inputs to Restaurant	calculated	kg N day^{-1}
Total food inputs to zone grocery	calculated	kg N day^{-1}
Total zone wastewater nitrogen	calculated	kg N day^{-1}
Total zone nitrogen to municipal solid waste actor	calculated	kg N day^{-1}

[1] (Cease, Capps et al. 2015)
[2] (USDA 2015)
[3] (Rose, Parker et al. 2015)
[4] (Wielemaker, Weijma et al. 2018)
[5] (Lundie and Peters 2005)
[6] (Gunders 2012)
[7] (USDA 2012)

The following equations are used to calculate nitrogen flows to and from the population actors in the zones. First, the total food purchased from groceries in the zone, both by restaurants and directly by population, is calculated using the total zonal population (TP), the per capita food nitrogen consumption rate and the food waste (FW). Total purchased food nitrogen is determined as follows:

$$N_{food} = \ food\ N\ consumed + food\ N\ wasted \tag{28}$$

where N_{food} is the total food purchased in the zone, for restaurant and residential purposes, $food\ N\ consumed$ includes all food eaten, both at restaurants and at home, and $food\ N\ wasted$ includes the total food waste produced per capita, including restaurants and at home. Using this value, the total nitrogen contents of wastewater (*WW N*), for the zone Population actors can be found using the food waste (*FW*) calculated (see APPENDIX A):

$$\begin{aligned} WW\ N\ &= (TP - YP)\left(N_{food}\right) + \left(YP \times 0.993 \times\ N_{food}\right) \\ &\quad + (TP \times FW) \times 0.025 \end{aligned} \tag{29}$$

where *TP* is total population, *YP* is youth population, and *FW* is total food wasted. Tabulated nitrogen flows calculated for all the zones can be found in Appendix A.

2. Restaurants:
   a. Restaurant inputs are calculated based on the percent of meals consumed out (32%) and corrected to include the additional food waste produced in restaurants (20.9%) (Gunders 2012, USDA 2012, USEPA 2012).
   b. All restaurants are assumed to be connected to the wastewater grid.

c. Food waste from restaurants either goes to wastewater treatment via sink food waste processor (5%) or to municipal solid waste (95%) (Lundie and Peters 2005).

The food inputs to Restaurant actors are calculated using the following information:

$$Food\ to\ Restaurant = (TP)\left(N_{food}\right)(\%\ of\ meals\ eaten\ out) \tag{30}$$

where TP is total population, N_{food} is the total food purchased in the zone (found using Equation 26 above), and the percent of meals eaten out is 32% (USDA 2012).

4.2.2.2 Waste Management Actors: Assumptions and Constants

Solid and liquid nitrogen wastes from the actors above are handled by county-level municipal solid waste (MSW) management and zone-level wastewater treatment plants (WWTP) or septic system actors in all scenarios. Each of the 15 county-level MSW actors collect and landfill of all solid waste produced by zone actors within their respective counties. As mentioned previously, WWTPs are present in every zone, and septic actors are also present in every zone in all 4 case studies. The assumptions and constants for each of these actors is outlined below.

1. Municipal Solid Waste (MSW) Management:
    a. MSW actors are present in all case studies at the county level.
    b. MSW actors collect from all zones in their counties and dispose of the sum of all food waste solids produced at the zone levels within the county. Sources of solid food waste:
        i. Population residential food waste that has not been disposed via sink

    ii. Restaurant solid food waste (not disposed via sink)
    iii. Grocery food waste (discussed below in 4.2.3)
  c. All inputs to MSW actors are sent to landfill in all scenarios.

2. Septic System Actors:
   a. Septic actors are present in every zone in all 4 scenarios.
   b. Septic actors receive nitrogen from population actors within their zone.
   c. Septic influent was determined to each zone septic actor based on the proportion of households with septic systems (Metropolitan North Georgia Water Planning 2006) multiplied by the sum of zone population residential food waste disposed via sink, urine, and feces (see Section 4.2.2.1).
   d. Outputs from septic actors include:
      i. Septage, sometimes referred to as septic solids, (15%) which is conveyed either for land application or to WWTP (AECOM 2009) based on reported averages (Van Drecht, Bouwman et al. 2009).
      ii. Effluent (85%), which leaches into the watershed (Van Drecht, Bouwman et al. 2009, Cease, Capps et al. 2015).

3. Wastewater Treatment Plants (WWTP):
   a. Nitrogen inputs and outputs are calculated using a mass-balance.
   b. WWTPs are present in every zone in all 4 scenarios.
   c. WWTPs receive nitrogen from population actors and restaurant actors within their zone.
   d. Primary WWTP influent was determined to each WWTP actor based on the sum of zonal population's residential and restaurant food waste disposed

via sink, plus all urine and feces from population actors (see Section 4.2.2.1), minus the population served by septic systems (in number 2 above).

e. A percentage of septage (see number 2 above) is then added to the WWTP nitrogen influent based on the percentage of residences with septic systems in each county and literature reporting the average percent (15%) of septic nitrogen that becomes septage (Metropolitan North Georgia Water Planning 2006, AECOM 2009, Van Drecht, Bouwman et al. 2009, Cease, Capps et al. 2015).

f. All nitrogen that enters WWTP leaves in one of 3 forms:

    i. Biosolids (15.6% of WWTP influent) are composed of filtered solids and microbial biomass produced during processing (AECOM 2009, Carey and Migliaccio 2009, Van Drecht, Bouwman et al. 2009). These are either land-applied (25% of solids), sent to an Incinerator actor (21% of solids), according to reported percentages (AECOM 2009).

    ii. Nitrogen gas (64% of WWTP influent nitrogen) is released by microbes from nitrification-denitrification as N_2 during bioprocessing (Baker, Hope et al. 2001, Carey and Migliaccio 2009, Van Drecht, Bouwman et al. 2009, Cease, Capps et al. 2015). This is considered a non-recoverable flow.

    iii. Effluent (20.4% of influent): once most nitrogen (79.6%) is removed in the forms above, the remainder takes one of three paths

(AECOM 2009, Van Drecht, Bouwman et al. 2009, Walker and Beck 2011):

1. Land-application (4% of effluent nitrogen – exported out of system boundary).
2. Recycled back into the water system (18% of effluent nitrogen – treated as background in mass balance).
3. Released as discharge downstream of drinking water sources (78% of effluent nitrogen – considered unrecovered dissipated flow).

The wastewater nitrogen fates are summarized in the material flow diagram in Figure 14. The percentages listed are the portion of nitrogen wastewater originating from population actors in each zone that are sent to wastewater treatment plants and septic actors, followed by the fates of influent nitrogen.

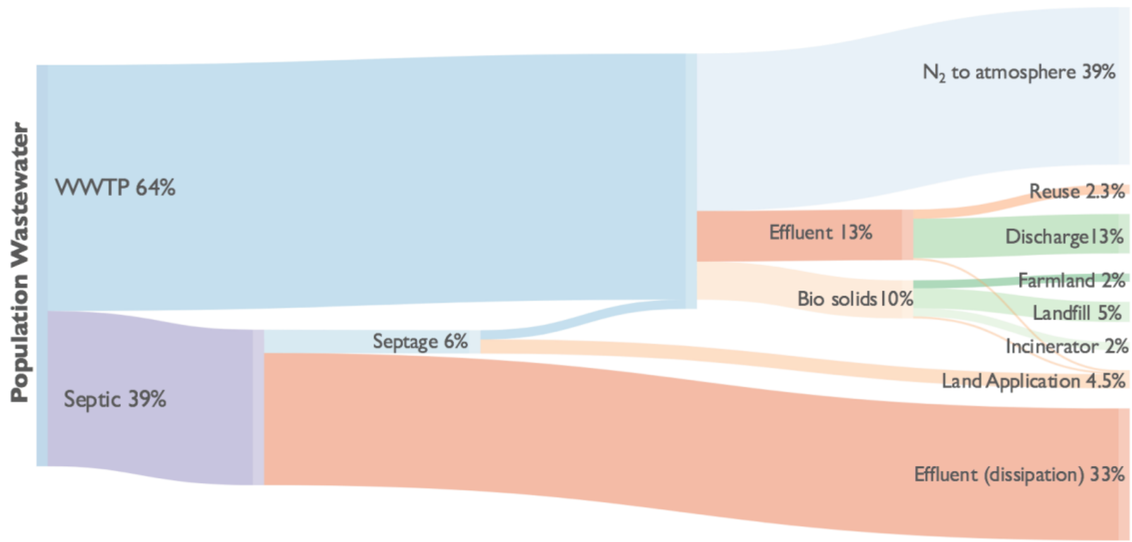


Figure 14: Wastewater nitrogen pathways and fates for population actors in all scenarios. Labels provide the pathways of each nitrogen fate as a fraction of the total population wastewater nitrogen.

As has been previously stated, the restaurant actors nitrogen flows are assumed to only go to the zone wastewater treatment plant (WWTP), thus following top level flows in Figure 14.

4.2.3 Variable Actors and Associated Nitrogen Flows (Task 1a)

In order to test the hypothesis that decentralized, urban farm food networks are more sustainable than urban food networks that do not source locally-grown food, the food distribution and production industries are modified in each of the case studies in this first experiment. The actors outlined in this section are the variable actors in the Agri-Network Centralization Experiment (ACE). These actors include actors within the produce farming and chemical fertilizer industries, poultry feed and poultry farming industries, and the food distribution industry (Figure 15). The following sections explain how the flows to, from, and between these actors change from case to case in the 4 ACE case studies.

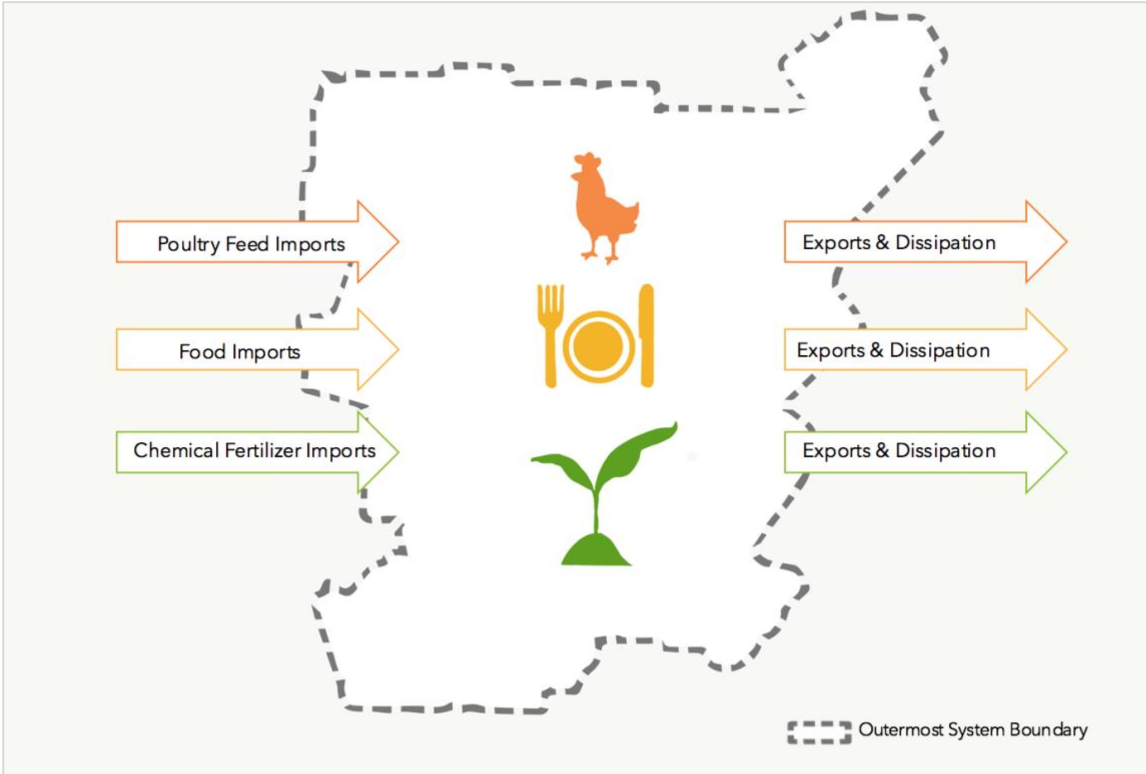


Figure 15: Variable actors in the ACE. Produce industry (green) and poultry industry (orange) actors interact with food distribution actors in different ways depending on the case study. Imports to the regional food distributor changes between the baseline (case 1) and the Urban Farm case studies (cases 2 – 4).

4.2.3.1 <u>Independent Variable Actors Assumptions and Constants: Cropland and Poultry</u>

Below are the guiding assumptions used for the cropland and poultry actors. Cropland inputs, yield, and waste products are calculated per-acre, while poultry is calculated per laying hen or broiler chicken. As mentioned previously in 4.2.1, data for agriculture productivity and inputs is reported in the literature as county-level totals. In order to make use of this county-level data, the 4 case studies follow one of three strategies:

- Disaggregate these totals using the Farmland Weighting Factor described by Equation 25 in Section 4.2.1 (Import/Export Case (IE – case 1) and Zone Urban Farm Case (ZUF – case 2)).
- Use reported county acreage and inventories (County Urban Farm Case (CUF – case 3)).
- Aggregate to regional totals (Region Urban Farm Case (RUF – case 4)).

The following two sections summarize the assumptions and constants used to establish flows to and from Cropland (1) and Poultry (2) actors.

1. <u>Cropland Assumptions</u>
    a. The cropland used in this study includes only the acreage onto which chemical nitrogen fertilizer is applied, reported per county in the literature (USDA 2014). Organic cropland, pastureland, and manure or compost-amended soil and crop yield is excluded from this study (see Appendix A for cropland acreage per county).
    b. All chemical fertilizer is imported to the system in all 4 case studies in Experiment 1, with uniformly-applied nitrogen fertilizer application rate (81.4 kg per acre), determined by USDA industry averages outlined in literature (Smil 1999, USEPA 2015).
    c. Crop yield is calculated based on average nitrogen yield per acre of the top 20 crops grown in Georgia (see Appendix A), corrected to exclude those crops that are grown in the southern part of the state (outside of the boundary) (USDA 2017).

d. Nitrogen uptake and volatilization rates were drawn from available literature (Smil 1997, Smil 1999, USEPA 2015).

e. All crop grown in the system boundary is considered edible to the human population.

Figure 16 shows the nitrogen inputs for the cropland and crop actors used in this study along with the outputs and their fates.

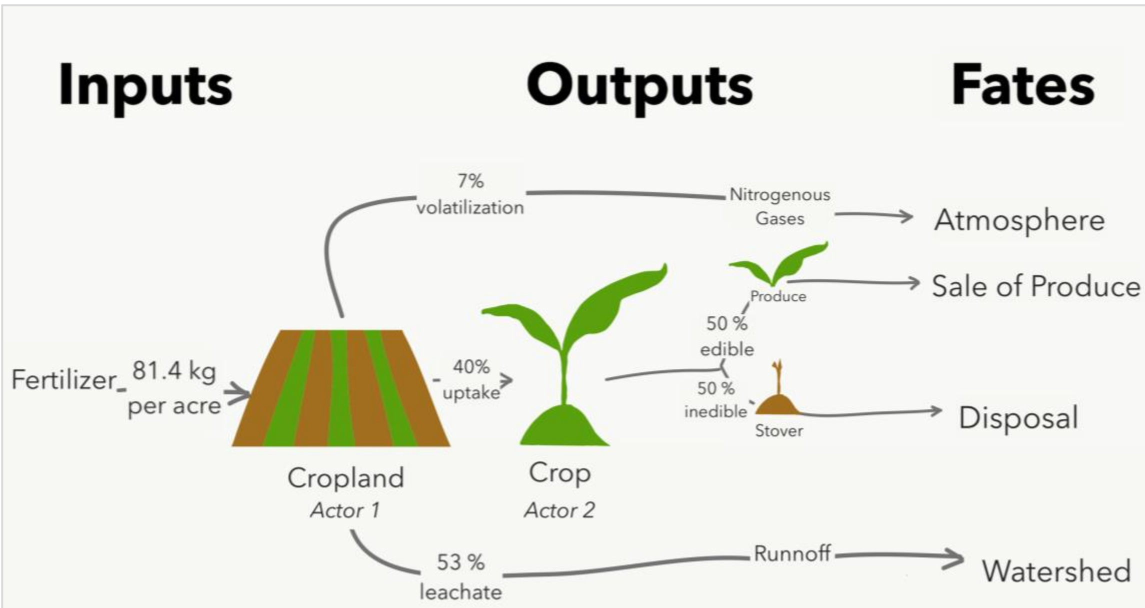


Figure 16: The produce farm is broken down into two actors, "cropland" and "crop." These actors' nitrogen (N) inputs, outputs, and fates are pictured above. Nitrogen inputs include only chemical fertilizer in the Agri-Network Centralization Experiment. Applied nitrogen is either volatilized (7%), taken up by plants (40%) or leached into local waterways (53%) (Smil 1997, Smil 1999, USEPA 2015, USDA 2017).

2. <u>Poultry Actors</u>

a. Poultry inventories are based on available broiler and layer inventories, reported per county (USDA 2014).

b. Broiler and layer feeding rates were established separately and multiplied by inventories of each in each county (Ravindran 2013).

c. Layers were assumed to produce one egg per day (Ravindran 2013).

d. Meat produced by layers is considered edible.

e. Poultry manure production and subsequent volatilization and leachate rates were drawn from literature (Cabrera and Gordillo 1995, Kellogg, Lander et al. 2000) and averaged per chicken.

f. Nitrogen assimilation per chicken was established based on averages reported in literature (Ritz and Merka 2013).

Figure 17 shows the nitrogen flows for each chicken used in this study.

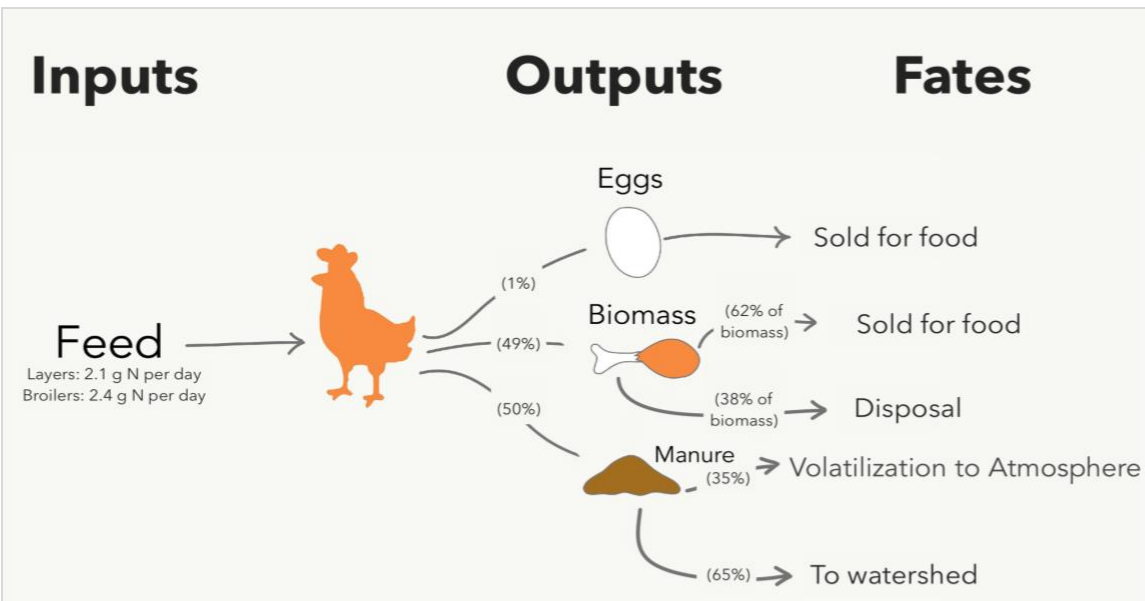


Figure 17: Poultry actor nitrogen (N) inputs, outputs, and fates. Feed inputs are either assimilated (50%) or evacuated (50%). Of the feed consumed, nitrogen either is converted into biomass (49%) or used to produce eggs (1%) (Cabrera and Gordillo 1995, Kellogg, Lander et al. 2000, Ravindran 2013, Ritz and Merka 2013).

In the Import/Export baseline case (IE – case 1), the distribution of produce and poultry product is managed by county-level produce and poultry product distributors, who collect these products from farms and convey them back up the hierarchy for sale outside the region. In the 3 urban farm case studies (cases 2-4), most poultry products are sold directly to food distribution actors at the level of cultivation (zone, county, or region levels), while surplus product is sent to produce and poultry product distributors up the hierarchy who sell to food distribution actors at their respective levels. This connectivity and redistribution to the food distribution actors for each of the 4 ACE case studies will be described in more depth with visualizations in Section 4.2.4.2.

4.2.3.2 Dependent Variable Actors Assumptions and Constants: Food Distributors

As stated previously, the total amount of food industry flows (except for those produced by farm actors) within the system are kept constant in case 1, the Import/Export Case (IE), case 2, the Zone Urban Farm Case (ZUF), case 3, County Urban Farm Case (CUF) or case 4, Region Urban Farm (RUF). These totals are dictated by the sum of the zone populations' consumption and waste, as outlined in Section in 4.2.2.

The food distributor industry actors include zone grocery stores, county food distributors, and regional food distributors. The overarching distribution hierarchy (Figure 18), from imported food (flow 1) down to county distributor (flow 2) and finally to zone grocery (flow 3), remains present in all 4 scenarios. However, the amount of eggs, meat, and produce products transferred via these pathways varies depending on each network's cropland and poultry actors. When available zone-grown, county-grown, or region-grown produce or poultry products are available at the same level as the grocery, county distributor, or regional distributor, respectively, these are prioritized. In the presence of Atlanta-grown food products in these instances, inputs from higher levels of the food distribution hierarchy are lessened by the amount of Atlanta-grown input. In the event that all nitrogen food equivalents from eggs, produce, and poultry meat can be supplied by farm actors, the flow from higher distribution levels goes to zero. (See Section 4.2.4 for further explanation.)

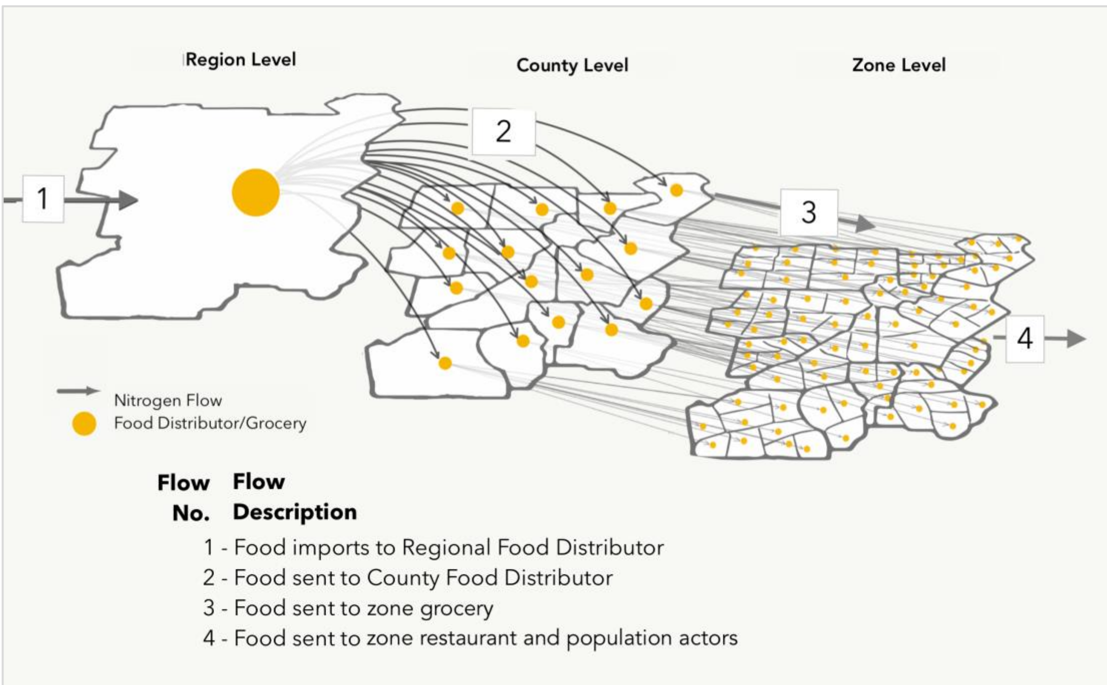


Figure 18: Food distribution hierarchy. Pictured, regional and county food distributors and zone grocery actors.

Assumptions and constants for total flows in and out of each of these food distributors are as follows:

1. <u>Grocery Stores (zones):</u>
    a. Grocery stores are present in all case studies, but the source varies depending on the farm actors' location.

b. Grocery stores receive inputs from the following actors (in corresponding case studies):

   i. County food distributor (IE, ZUF, CUF, RUF)

   ii. Zone crop or poultry farmland (ZUF only)

c. Total input nitrogen to grocery remains the same in all case studies, determined in magnitude by the following:

   i. Using the per-capita consumption and food waste patterns established above (Section 4.2.2), population purchasing is then determined based on consumption calculated adjusting for residential and restaurant food waste.

   ii. Grocery stores are then assumed to waste an additional (9.5%) of food (FAO 2011, Gunders 2012)

   iii. Grocery inputs are then calculated to meet the consumption needs of the population based on 2a and 2b.

d. Grocery outputs are sent to restaurants or directly to population based on demographic averages (see 4.2.2) (USDA 2012):

   i. Percent consumed out (32%)

   ii. Percent consumed at home (68%)

2. <u>County Food Distributors (county level):</u>

   a. County food distributors are present in all case studies, but their sources of food vary depending on the location of farms in the case study (see c).

b. County food distributors receive the same amount of total food in each case study, equal to the total food required by the sum of all grocery stores within said county.

c. Food inputs to county food distributors come from the following actors (in each case study):

    i. Regional food distributor (IE, ZUF, CUF, RUF)

    ii. County produce or poultry product distributors (ZUF only)

    iii. County crop or poultry farm (County Urban Farm Case)

d. Food outputs from county food distributors go to each of the zone grocery stores within the respective county, based on remaining need of the grocery, determined by the following (in each case study):

    i. All food required by zone grocery (IE, CUF, RUF)

    ii. All food required minus whatever has been supplied by zone poultry and zone produce farms (ZUF only)

3. <u>Regional Food Distributor (region level):</u>

    a. Regional food distributors are present in all case studies, but their input source varies depending on the farm actors' locations.

    b. Regional food distributors receive the same amount of total food in each case study, equal to the total food required by the sum of all county food distributors in the region.

    c. Food inputs to regional food distributor comes from the following actors (in each case study):

        i. Direct Imports (IE, ZUF, CUF, RUF)

ii. Region Urban Farms (RUF only)

iii. Regional produce and poultry product distributors (ZUF, CUF)

A more detailed summary of food input sources to the three food distribution levels in each of the 4 case studies can be found in Section 4.2.4 below.

4.2.4 Network Construction: Connections and Flows Between Actors

After each of the actors and their nitrogen inputs and outputs are determined, the connectivity between actors is established based on the available data and assumptions outlined in Section 4.2.2 above. The following sections describe first the connectivity between constant actors (Section 4.2.4.1), and then the connectivity between variable actors in the baseline case study (Section 4.2.4.2) and urban farm scenario case studies (Section 4.2.4.3).

4.2.4.1 <u>Flows Between Constant Actors in All Case Studies</u>

As mentioned in Section 4.2.2, all flows of food into the zone food supply come through the zone grocery store actor, which in turn sends its inputs to either restaurants or directly to population actors within the zone. (The source of inputs zone groceries will be discussed in the following section, 4.2.4.2). Figure 19 shows the connectivity of the restaurant, population, and waste management actors within a zone, along with thee food waste and human waste destinations.

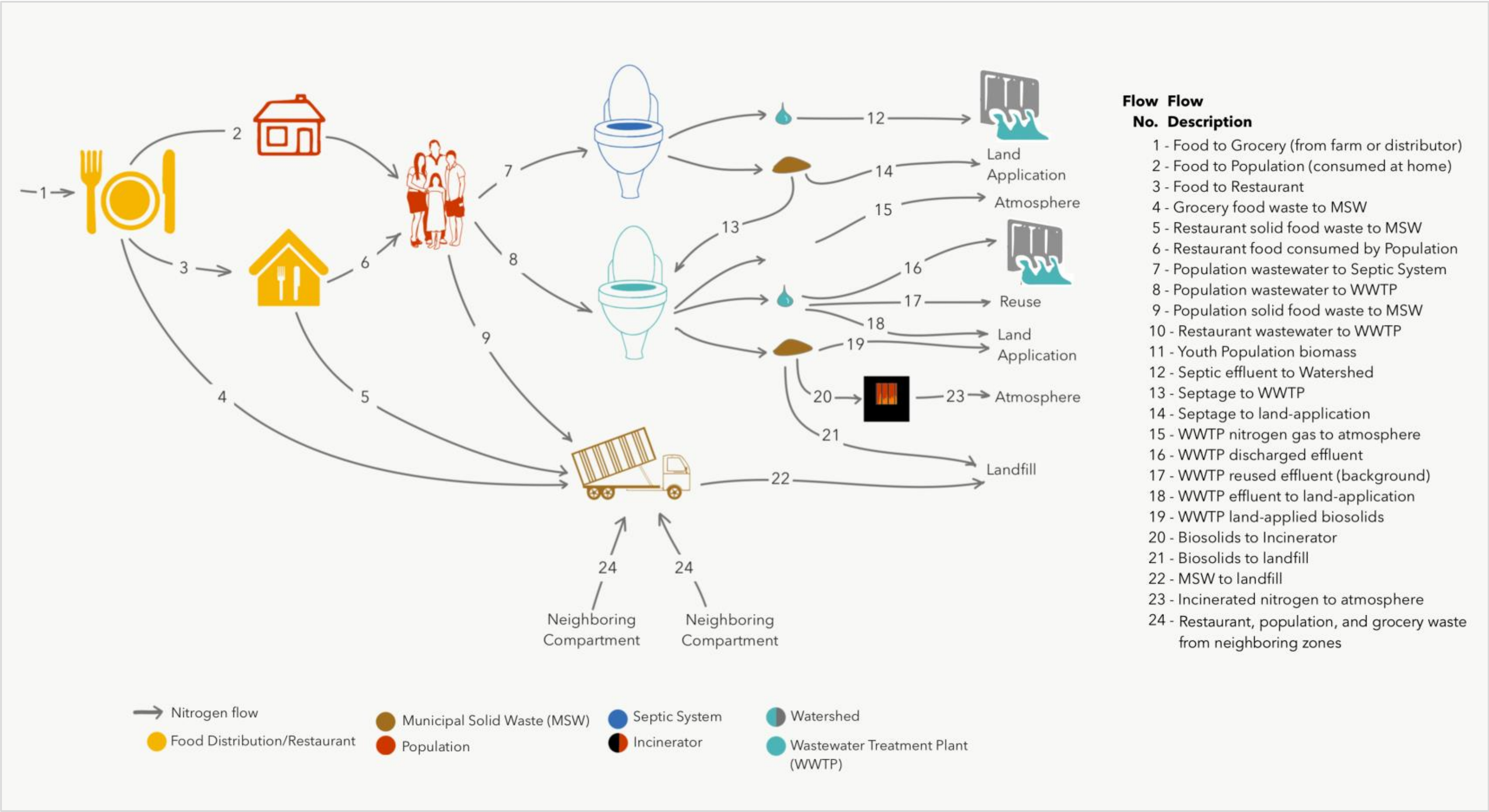


Figure 19: Constant flows of nitrogen in all case studies in the Agri-Network Centralization Experiment. Flows are numbered 1-24 and described on the right. Flows into zone grocery (flow 1) come from either farms or county distributors, depending on the case study and farm productivity (see Section 4.2.4.2)

The magnitude of nitrogen that comes out of the grocery is determined according to the sum of population's food requirements (waste + consumed), and this magnitude is held constant in every case study. The population receives food either directly from grocery stores (68% - flow 2) or from restaurants (32% - flow 6). To later calculate the amount of food inputs to each Food Distribution Actor that could be offset by the poultry and produce actors in the subsequent Urban farm Case Studies, (Task 1c), it is also necessary to calculate the percentage of food consumption that comes from eggs (4.4%), meat (84.7%), and fruits or vegetables (10.9%) (WHO/FAO 2002, Cease, Capps et al. 2015). Food flows were thus divided into these three categories, which were then used to determine the amount of produce product or poultry product that should be supplied by each type of farm actor.

Flows that are received by waste management actors include solid and liquid waste (see Section 4.2.2). Solid waste goes to county-level municipal solid waste management actors (MSW), and waste water, including sink food waste and human waste liquids and solids, goes to zone-level wastewater treatment plants (WWTP) and septic actors. Figure 19 also shows the inflows of nitrogen to these wastewater actors and the connectivity between septic and WWTP actors in each zone. Also pictured are the nitrogen outputs and destinations from each actor.

4.2.4.2 Flows Between Variable Actors: Baseline Scenario (Case 1)

The flows and the connectivity between constant actors in Section 4.2.4.1 remain the same in all 4 case studies. However, as mentioned previously, the flows and connectivity between variable actors, including poultry industry and produce industry actors and food distribution actors, change between the 4 case studies. The following subsections describe the connectivity between independent (produce and poultry industries) and dependent variable (food distribution industry) actors for each of the 4 case studies in the Agri-Network Centralization Experiment.

First Case Study: Import/Export Case Baseline (Task 1b)

The baseline configuration is constructed with the realization that a very large percentage of the food consumed in Atlanta is brought in from surrounding states and even international sources. This is based on studies characterizing food flows into and out of the region along with calculations made in this study regarding the relative import magnitudes as they compare to estimated consumption magnitudes. For example, the Atlanta-Sandy Springs-Gainesville statistical area has strong node in-strength (ranked 9th domestically according to the 2007 Commodity Flow Survey (US Census Bureau 2007)) in the national food supply network (Lin, Dang et al. 2014), indicating that it is a heavy importer of food flows as compared to the national average. Lin et al. found total of 8.6 million tons of foodstuffs was imported in 2007 (Lin, Dang et al. 2014). Meanwhile, the same study found that most of food produced in the region is exported outside of the region. Therefore, for the baseline case, all food required by the region's population is imported to satisfy the requirements of the zone population and all farm products are exported from the region.

Figure 20 illustrates the parallel trajectories of poultry feed and farm actors (orange), food flows between food-sector actors (yellow), and chemical fertilizer and produce farm actors (green) used for the Import/Export Case.

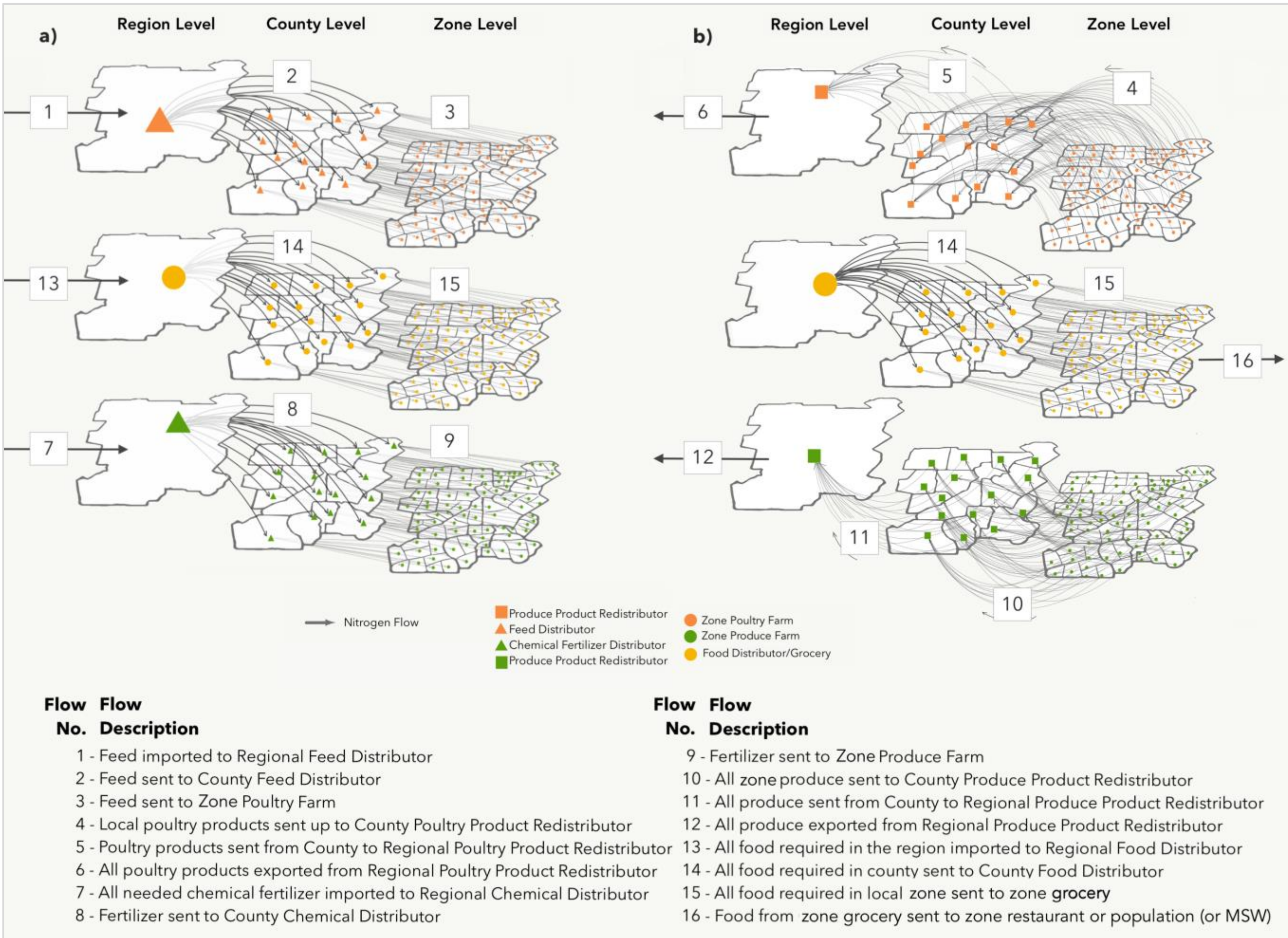


Figure 20: First Case Study Part I (Import/Export Case – IE) independent and dependent variable flow paths down to zones (a - left) and from zones (b - right). Flows are numbered sequentially, and flows 14 and 15 are identical in a and b.

Once imported to the region-level distribution hubs, food, fertilizer, and feed move to county-level warehouses according to purchasing requirements of population and farm actors within the county (see Sections 4.2.2 and 4.2.3 above) (MWPVL 2010, USDA 2012, USDA 2014, USDA 2017). Food and farm goods pass through the Regional Food Distributor, and then they are delivered by the county-level distribution actor intermediaries to their final zone-level destinations by truck (MWPVL 2008). Next, feed moves to poultry operations and poultry actors, fertilizer is added to cropland and is taken up by crops, and then poultry and produce products at the zone level are then conveyed back up the supply chain, aggregated by county distribution centers and prepared for further aggregation at the regional level and then exported for shipment outside of the region boundary.

These flows represent the baseline configuration in which all food grown within the system boundary is conveyed out via regional produce and poultry product distributors and exported for consumption outside of the region. The pictured network is then modified into the 3 Urban farm Scenarios presented by case studies 2-4.

As mentioned previously, the flows from groceries to zone restaurants and population actors are constant flows (see Section 4.2.4.1 above).

4.2.4.3 Flows Between Variable Actors: Urban farm Scenario (Cases 2-4) (Task 1c)

In the following 3 additional Urban farm case studies, imports of food to the region and exports of food products from Cropland and Poultry actors are reduced, favoring nutrient retention within the system boundary. Rather than importing all food and exporting all agricultural products, farm products are sent directly to food distribution actors. In Case

2, the Zone Urban Farm Case (ZUF), food and farm flows from Case 1 (IE) remain the same, but rather than exporting produce and poultry products, food products grown within the zone are primarily sent directly to zone grocery actors. In Case 3, the County Urban Farm Case (CUF), zone farms' inputs, waste, and productivity are aggregated into more centralized county farms, which in turn supply food to county food distributors. Finally, in the Region Urban Farm Case configuration, zone and county farm and poultry actors are removed and replaced by centralized farmland and poultry industry actors. Connectivity and flows for the 3 additional case studies' independent (crop and poultry industries) and dependent (food industry) variable actors are illustrated in the following subsections. In all of the following representations, "crop" and "cropland" actors are consolidated into a "produce farms" in order to simplify the diagrams. (Please refer to Figure 16 on page 94 for the breakdown of the cropland and crop actors.)

Second Case Study: Zone Urban Farm Case (ZUF)

The Zone Urban Farm Case (ZUF) is nearly identical to the Import/Export Case, apart from the flows between farm and food distribution actors. As the least centralized version of the network, the Zone Urban Farm Case (ZUF) follows similar distribution trajectories for imported fertilizer and poultry feed down to zone farms as in the baseline configurations (Figure 20a. on page 104). However, once farm goods are produced, zone Cropland and Poultry actors sell directly to Grocery actors at the zone level rather than selling all the produced goods up the hierarchy and out of the regional boundary. These flows are calculated to satisfy the food requirements within each zone as dictated by the sum Population and Restaurant flows of food and waste, which remain the same in all configurations (see 4.2.2). Any surplus food produced at the zone level is sent up to the county level.

In the Zone Farm Case, excess food products are still sent up the chain to county actors, which then can sell to county-level food distributors until county needs are met. As described previously (see Section 4.2.3), the total magnitude of flows into and out of food distribution actors remains constant, but the presence of linkages (sources of food flows) and the magnitude of individual food flows between food distributor actors (yellow nodes) is dependent on the amount delivered by farm industry actors in each of the case studies. These flows are illustrated in Figure 21.

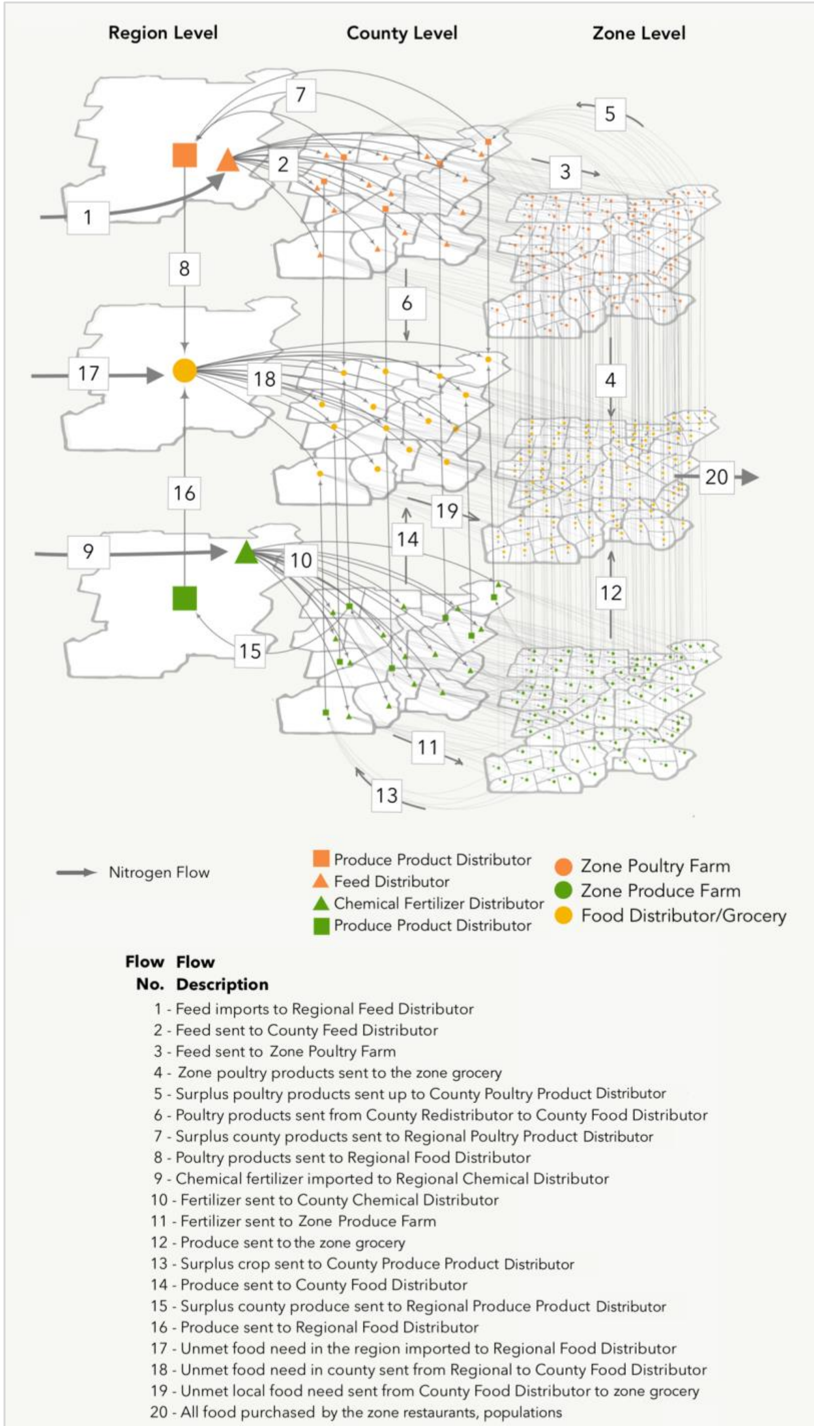


Figure 21: Zone Urban Farm Case Study (ZUF) flows between variable actors. Farm products move from poultry actors (orange) and produce actors (green) to food distributors (yellow). Flows between food distributor actors (flows 17-19) are decreased from the baseline by flows from farm actors. Flows from zone groceries to restaurants and populations (Flow 20) remain unchanged from the baseline. Cropland and Crop actors are condensed in this representation.

Third Case Study: County Urban Farm Case (CUF)

The County Urban Farm Case (CUF) is similar to the first 2 case studies, the baseline (IE) and Zone Urban Farm (ZUF) cases; however, all the poultry and produce production that occurs within the zone in the IE and ZUF cases are accumulated into more centralized county-level poultry and produce farms in the third case study (CUF). The new pathways are illustrated in Figure 22, which shows the feed and fertilizer flows alongside food flows and the transfer of poultry and produce products to the food distribution hubs.

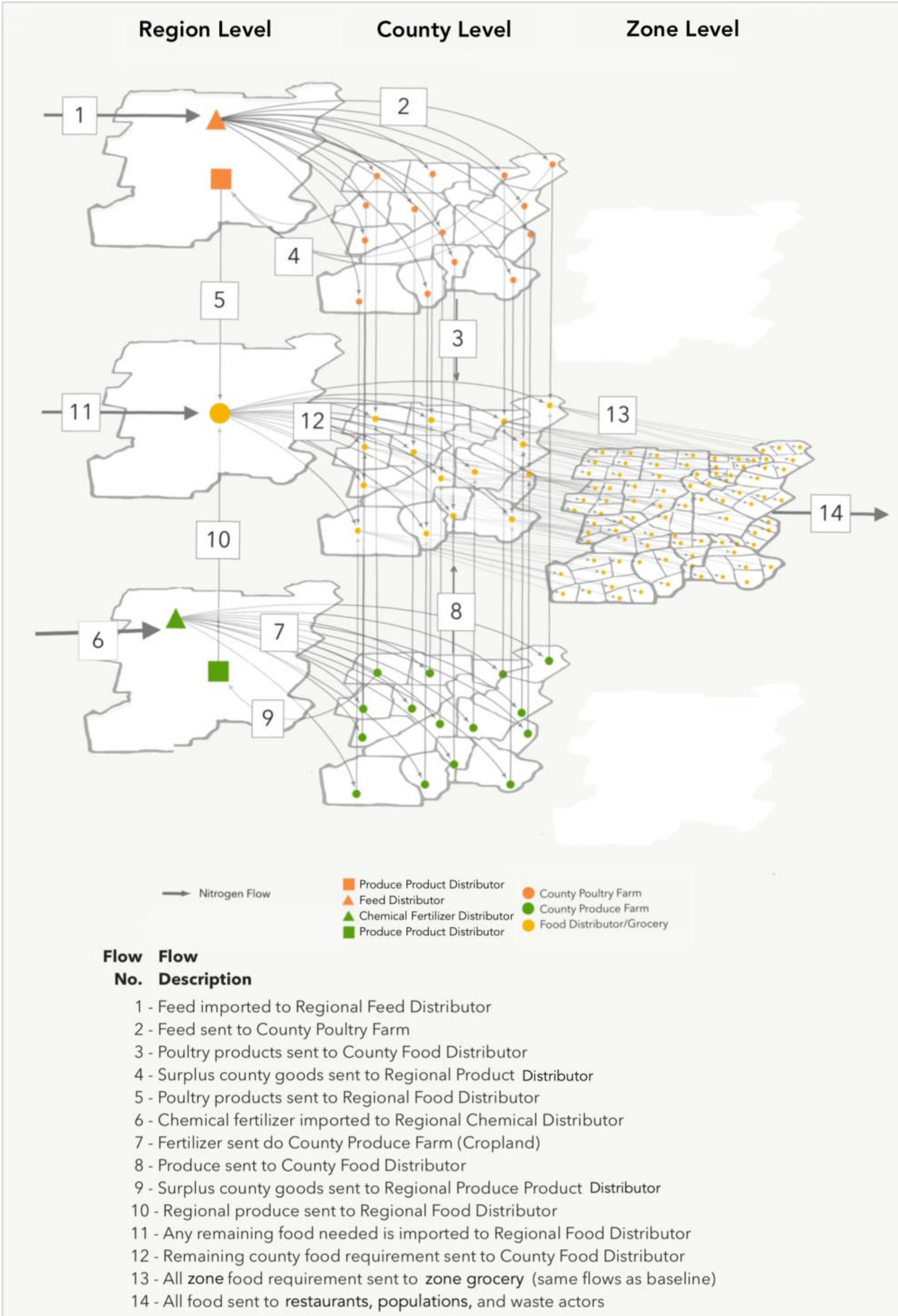


Figure 22: County Urban Farm Case Study (CUF) variable flows between Poultry (orange), Produce (green) actors and food distribution actors (yellow). Flows of food into the Regional Distributor (flow 11) is lessened from the baseline by farm product inputs. Cropland and crop actors are condensed for the representation

The food flows (yellow) in are slightly different from those seen in the baseline case (IE). Flows from the county food distributor to zone grocery actors are the same in magnitude as those from food warehouse to zone grocery in the baseline case. However. the flows to the county food distributor from the regional food distributor (Figure 22, flow 12) are lessened by the magnitudes of poultry and produce products produced within the county. Likewise, imports are lessened by any food products that are transferred from the poultry and produce nodes to food nodes. As in the Zone Urban Farm Case, any magnitudes of food into and out of yellow food nodes are maintained and are dictated by the zone population requirements.

Fourth Case Study: Region Farm Case

Figure 23 illustrates a geographical network visualization of the Region Urban Farm Case (RUF – case study 4). The green node represents the cropland actor that receives chemical inputs into centralized, regional farmland (crop and cropland actors are consolidated into a "produce farm" in this representation), orange nodes are poultry actors, and yellow nodes represent the food distribution hierarchy, which remains unchanged from the baseline case, except for the import flows (flow 5), which is lessened by the magnitude of flows that come from crop and poultry actors.

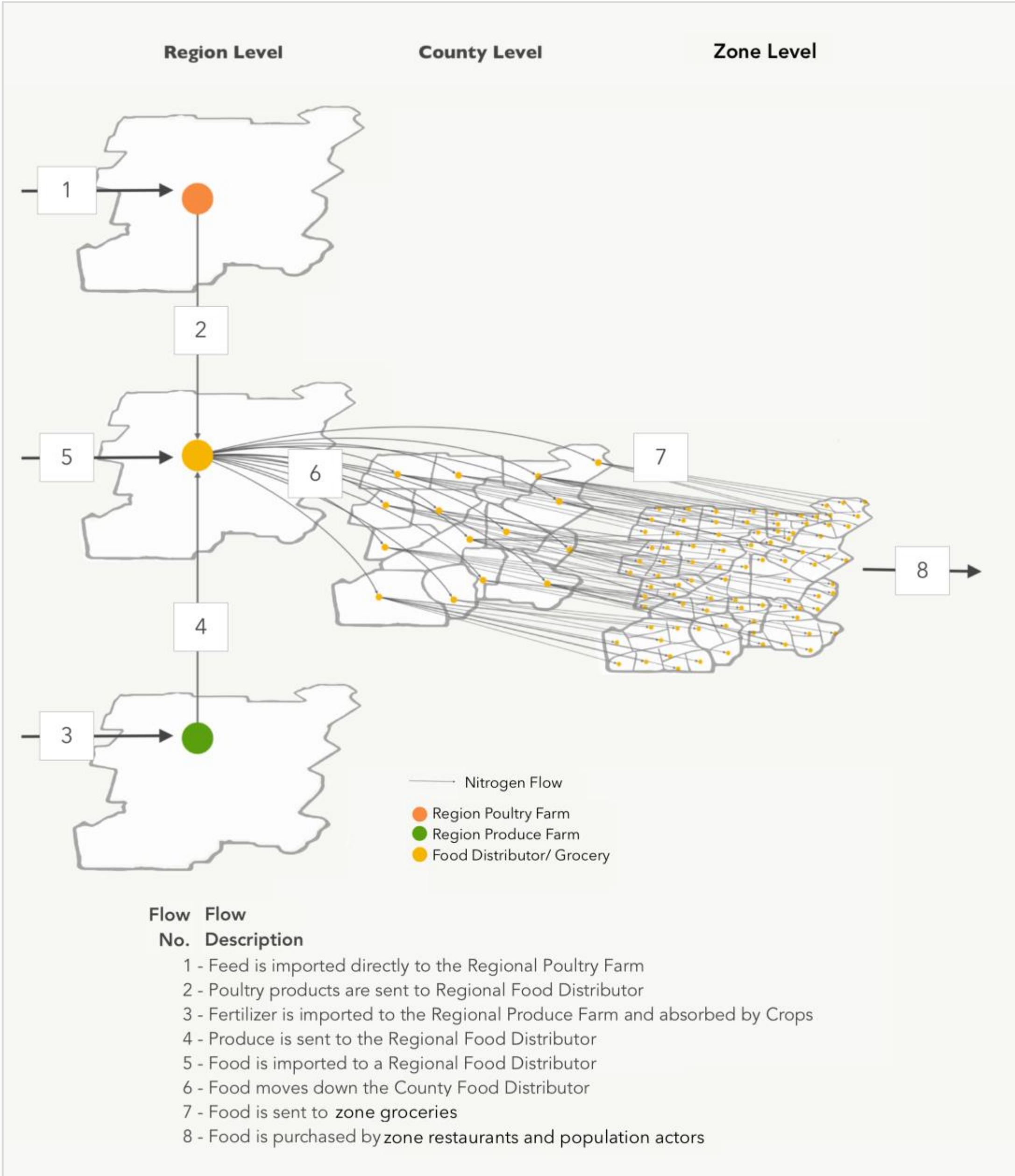


Figure 23: Region Urban Farm Case Study (RUF) variable flows. Poultry farm (orange) and produce farm (green) actors alongside food distribution pathways (yellow). Import magnitude (flow 7) is reduced from the baseline (Case 1 – IE) by the combined magnitude of flows from region farms (flows 2 and 4), but is the same as food imported to the regional food distributor in the Zone and County Urban Farm Cases. (Note: "Produce farm" represents the sum of cropland and crop actors.)

Also seen in this network are the yellow food distributor actors, representing regional and county food handlers, and zone-level groceries. Here, food products are cultivated at the regional level. Then this food changes hands to food distributors at the regional level. Food products from the regional distributor are transferred to county warehouses for distribution to zone-level groceries. In the Region Urban Farm configuration, connectivity and flow magnitude between regional food distribution actors and down are the same as the baseline (Case 1 – IE).

4.2.5 Analysis of Case Studies (Task 1d)

Following the construction of each network case study (Tasks 1a-c), the 4 case studies are then analysed with respect to their input flows, internal flows, exports, and waste flows, as well as their network structure and flow metrics using methods outlined in the Ecological Network Analysis section in Section 3.1.

Next, imports, exports and waste flows are then compared between the baseline and the urban farm scenario to illustrate the relative changes to environmental impacts from food miles brought on by a shift to urban farm food procurement.

4.2.5.1 <u>Network Analysis</u>

First, the ecological network metrics are determined for each of the 4 case studies using the following steps:

1. Flows from and to each actor are tabulated in excel for each of the 4 case study networks.
2. Using MATLAB, the excel spreadsheets are converted into N+3 x N+3 formatted arrays with N actors and their corresponding flow values, to which imports, row 0,

and exports and dissipation (rows N+1 and N+2, respectively) are added, as described in Section 3.1.2.

3. The corresponding "flow matrix" produced is then converted into an adjacency matrix, or "structure matrix," with 1's replacing any weighted values.
4. Using the Ecological Network Analysis (ENA) methods described in Chapter 3, both structure and flow metrics are calculated for each of the 4 case studies using the "flow" and "structure" matrices.
    a. Twelve ecological structure metrics are calculated: Species Richness (*n*), Number Of Links (*L*), Connectance (*C*), Linkage Density (L_D), Prey (n_{prey}), Predators ($n_{predator}$), Prey-Predator Ratio (P_R), Number of Specialized Predators ($n_{s\text{-}Predator}$), Fraction of Specialized Predators (P_S), Vulnerability (*V*), Generalization (*G*), and Cyclicity (λ_{max}).
    b. Nine ecological flow metrics are calculated: Finn's Cycling Index (*FCI*), Mean Path Length (*MPL*), Average Mutual Information (*AMI*), Ascendency (*ASC*), Development Capacity (*DC*), Total System Overhead (*TSO*), Total System Throughflow (*TST*), *ASC/DC*, and Robustness (*R*).

Following the computation of ENA metrics, the structure matrix found in step (2) above is used to determine the structural centralization of each of the urban farm case studies (cases 2-4). Centralization is calculated for each network using the relationship between centrality of each actor, as described in Section 3.2. Given the size of the networks, the open source software environment known as Cytoscape is used to perform this task (Freeman 1978, Shannon, Markiel et al. 2003).

Next, Using the ENA metrics calculated for each of the networks, the ENA metrics are compared to existing food web median values (Layton 2014). The urban farm case studies are then compared using their centralization scores, and ENA metrics are plotted against centralization in order to detect trends that may exist between the network indices.

4.2.5.2 Quantification of Food Miles Reduction from Urban Agriculture

In the urban farm scenario (cases 2 – 4), imports of egg, meat, and produce are reduced into the system boundary by retaining the food produced inside the system boundary rather than exporting it. Once the flow change afforded by urban farm is calculated, LCA is then conducted on transportation of produce, meat, and egg imports into the baseline and urban farm scenario. The study uses the national regions that produce most of the nation's food products and the miles from these to Atlanta to approximate the impact food miles embedded in imported food products. Node out-strength from literature is used as a benchmark for the proportion of food imported to Atlanta from outside to approximate which regions should be included as the sources of food products, as well as the percentages of food products obtained from each of these.

It is assumed that food products are transported using climate-controlled trucks. In order to populate individual process inventories, namely the mileage traveled and weight of imports, this study leverages the node out strength (s_{out}) from earlier network analysis of food flows within the United States (Lin, Dang et al. 2014), and N contents by weight from the literature (USDA 2015). Table 5 illustrates how the total food miles were calculated using node s_{out}.

Node out-strength is calculated using the weight of any edge connecting to a node, and the out-strength specifically measures the weight of directed flows from a given node. The values of the top 5 producers, ranked by their out-strength, along with their relative proportions of the total, along with these regions' distance to the Atlanta region, can be found in Table 5.

Table 5: Food miles calculation using node out strength (Lin, Dang et al. 2014) to determine proportion of food imported and miles traveled to the Atlanta Region.

Top 5 US Agriculture Producers	S_{out}	Proportion of total node out-strength*	Distance to Atlanta (miles)
Iowa	31.6	0.273	1444
Illinois	28.3	0.244	1102
Missouri	20.8	0.180	1063
Nebraska	18.1	0.156	1902
California	17	0.147	4138
Total S_{out}:	**115.8**	**Total food miles:**	**1759.06**

***Used as assumed value for portion of all food imports to Atlanta from each of the top 5 producers listed in column 1.**

The LCA uses SimaPro 8.2.3, leveraging inventory data from Agri-Footprint 3.0, Ecoinvent 3, Industry Data 2.0, and USLCI. Using the locations above and their distances from the Atlanta Metropolitan Region, combined with the total weights of each of the food products and the magnitudes imported in the baseline and urban farm case studies, LCA impacts are calculated using ReCiPe's (H) 2016 endpoint assessment.

Results from the network analysis and life cycle impact assessments of imported foods are first reported in Section 4.3 and then discussed and compared in Section 4.4.

4.3 Results

This study examines nitrogen flux into, around, and out of the Atlanta Region. Modifications are made to existing urban and industrial agriculture and waste management actors drawn from the literature. Four urban food network models are first established with the same basic actors. These actors, modeled based on the existing components of the food supply chain into and around the Atlanta Region and the existing waste management infrastructure (AECOM 2009, USDA 2012, USDA 2014), are connected using varying degrees of centralization for food production and distribution within the network.

This section presents the results of the network analysis and import life cycle impact assessment. First the baseline case study results are presented, followed by the urban farm case studies and finally the life cycle impacts of the baseline and urban farm scenarios. These results will then be discussed together and compared to natural ecosystems in Section 4.4, where all 4 case studies are analyzed with respect to ecological network performance and compared to existing food web median values from the literature (Layton 2014).

4.3.1 Baseline Case Study (Import/Export – IE) Results

The Import/Export (Case 1) models a system in which no urban farm, defined as locally-sourcing food from agriculture production within the system boundary, is analysed first with respect to ecological network indicators described in Section 3.1.

Twelve ecological structure-based metrics are calculated using the equations outlined in Section 3.1.1. These structure metrics include: Species Richness (n), Number Of Links (L), Connectance (C), Linkage Density (L_D), Prey (n_{prey}), Predators ($n_{predator}$), Prey-Predator Ratio (P_R), Number of Specialized Predators ($n_{s\text{-}Predator}$), Fraction of

Specialized Predators (P_S), Vulnerability (V), Generalization (G), and Cyclicity (λ_{max}). These ENA metric results are then compared against food web medians from literature (Layton 2014). These results can be found for IE in Table 6.

Table 6: ENA structure-based metric results for the baseline case study (Import/Export – Case 1).

Case Study	N	L	L_D	C	n_{Prey}	$n_{Predator}$	P_R	λ_{max}	$n_{s\text{-}predator}$	P_s	V	G
1 - IE	883	2613	1.68	0.003	880	881	0.999	0	654	0.75	2.68	2.68

IE – Import/Export Case (Case 1)

n – number of species (species richness)
L – number of links
L_D – linkage density
C – Connectance
n_{prey} – Number of Prey
$n_{predator}$ – Number of Predators
$n_{s\text{-}predator}$ – Number of Specialized Predators
P_R – Prey to Predator ratio
λ_{max} – Cyclicity
P_s– Fraction Specialized Predators
V – Vulnerability
G – Generalization

Using the flow matrix and ENA indices described in Section 3.1.2, nine flow-based metrics are calculated including: Finn's Cycling Index (*FCI*), Mean Path Length (*MPL*), Average Mutual Information (*AMI*), Ascendency (*ASC*), Development Capacity (*DC*), Total System Overhead (*TSO*), Total System Throughflow (*TST*), Efficiency (*ASC/DC*), and Robustness (R). These flow-based metric results for the Import/Export case study can be found in Table 7.

Table 7: ENA flow-based metric values for Import/Export (case 1).

Case Study	*FCI*	*MPL*	*AMI*	*ASC*	*DC*	*TSO*	*TST*	*ASC/DC*	*R*
1 - IE	0	4.97	5.11	$1.57\text{x}10^9$	$2.46\text{x}10^9$	$8.96\text{x}10^8$	$2.55\text{x}10^8$	0.64	0.42

IE – Import/Export Case
FCI – Finn's Cycling Index
MPL – Mean Path Length
AMI – Average Mutual Information
DC – Development Capacity
TSO – Total System Overhead
TST – Total System Throughflow
ASC/DC – Ascendancy over Development Capacity
R - Robustness

The sum of yearly imports of nitrogen to Produce, Poultry, and Food Distribution Industries in the Import/Export (IE) case study amount to 51.36 million kilograms. This is shown alongside the total internal flow, exports, and dissipated flows in the IE network in Table 8.

Table 8: Import/Export (case 1) magnitudes of imported, internal, exported, and dissipated nitrogen flows (values are given in units of kg N y^{-1}).

Case Study	Imports	Internal Flows	Exports	Dissipation
1 – IE	5.136×10^{7}	2.037×10^{8}	7.431×10^{6}	4.393×10^{7}

IE – Import/Export Case

These results, along with the results described in the following section, will be discussed in Section 4.4.

4.3.2 Urban farm Case Study Results

After the baseline is established in which all food is imported and all farm products are exported in 4.3.1, the urban farm scenario case studies from Task 1care evaluated. First, all 3 urban farm scenario case studies, including the Zone Urban Farm Case (ZUF – case 2), the County Urban Farm Case (CUF – case 3), and the Region Urban Farm Case (RUF – case 4), were evaluated using the ecological network indicators described in Section 3.1. The same twelve ecological structure-based metrics used to evaluate the Import/Export case study (IE – case 1) were calculated using the equations outlined in Section 3.1.1. These include: Species Richness (n), Number of Links (L), Connectance (C), Linkage Density (L_D), Prey (n_{prey}), Predators ($n_{predator}$), Prey-Predator Ratio (P_R), Number of Specialized

Predators ($n_{S\text{-}Predator}$), Fraction Specialized Predators (P_S), Vulnerability (V), Generalization (G), And Cyclicity (Λ_{max}). The results can be found in Table 9.

Table 9: ENA structure-based metric results for case studies 2-4 in Agri-Network Centralization Experiment.

Case Study	N	L	L_D	C	N_{Prey}	$N_{Pred.}$	P_R	λ_{max}	$N_{s\text{-}pred.}$	P_s	V	G
2 - ZUF	883	2632	2.981	0.003	863	864	0.999	0	563	0.652	3.05	3.05
3 - CUF	780	1842	2.362	0.003	606	607	0.998	0	395	0.651	3.04	3.03
4 - RUF	659	1695	2.572	0.004	558	559	0.998	0	366	0.655	3.04	3.03

ZUF – Zone Urban Farm Case
CUF – County Urban Farm Case
RUF – Region Urban Farm Case

n – number of species (species richness)
L – number of links
L_D – linkage density

C – Connectance
n_{prey} – Number of Prey
$n_{predator}$ – Number of Predators
$n_{s\text{-}predator}$ – Number of Specialized Predators
P_R – Prey to Predator ratio
λ_{max} – Cyclicity
P_s– Fraction Specialized Predators
V – Vulnerability
G – Generalization

Using the flow matrix and ENA indices described in Section 3.1.2, the same nine flow-based metrics used to quantify the IE network are calculated for the urban farm scenario case studies. These metrics include: Finn's Cycling Index (*FCI*), Mean Path Length (*MPL*), Average Mutual Information (*AMI*), Ascendency (*ASC*), Development Capacity (*DC*), Total System Overhead (*TSO*), Total System Throughflow (*TST*), *ASC/DC*, and Robustness (*R*). These flow-based metric results for the 3 urban farm case studies can be found in Table 10.

Table 10: ENA flow metric results for urban farm scenario case studies

Case Study	*FCI*	*MPL*	*AMI*	*ASC*	*DC*	*TSO*	*TST*	*ASC/DC*	*R*
2 - ZUF	0	5.26	5.14	1.46×10^{9}	2.31×10^{9}	8.52×10^{8}	2.39×10^{8}	0.63	0.42

Table 10 (Continued)

3 - CUF	0	4.89	4.84	$1.29x10^9$	$2.08x10^9$	$7.83x10^8$	$2.22x10^8$	0.62	0.43
4 - RUF	0	4.60	4.53	$1.15x10^9$	$1.90x10^9$	$7.42x10^8$	$2.09x10^8$	0.61	0.44

ZUF – Zone Urban Farm Case
CUF – County Urban Farm Case
RUF – Region Urban Farm Case

FCI – Finn's Cycling Index
MPL – mean path length
AMI – average mutual information
DC – development capacity
TSO – total system overhead
TST – total system throughflow
R - robustness

Once the ENA metric values are determined, the 3 urban farm cases are analysed with respect to their degree of centralization, computed using Freeman's centralization metric, as defined in 3.2, using the Network Analyzer tool in Cytoscape (Freeman 1977, Shannon, Markiel et al. 2003). Next, the ENA structure and flow metrics are found for the 3 additional case studies in ACE, following the procedures outlined in Section 3.1.1, and these results are plotted against the degree of centralization for each of the 3 case studies. The degree of network centralization for each of the 3 urban farm scenario case studies are found in Table 11.

Table 11: Network centralization results for the 3 urban farm scenarios case studies (2, 3 and 4) alongside the baseline (IE – case 1).

Case Study	Centralization
1 – IE	0.20
2 – ZUF	0.20
3 – CUF	0.165
4 – RUF	0.308

IE – Import/Export Case
ZUF – Zone Urban Farm Case
CUF – County Urban Farm Case
RUF – Region Urban Farm Case

What becomes immediately apparent from Table 11 is that the 3 urban farm cases, ZUF, CUF, and RUF, do not follow the originally intended pattern of increasing centralization, as constructed. The CUF (County Urban Farm) case appears to be the least centralized network, contrary to the fact that it has fewer, more centralized farms than the ZUF (Zone Urban Farm) case, which was intended to be the least centralized network. It turns out that the presence of basin actors skews the centralization scores by acting as strongly-connected actors, especially in the presence of many smaller farm actors, which are present in ZUF. This actor designation will be discussed in more detail, along with the resulting consequences to ENA metric values, in Section 4.4.

Following calculation of the centralization metrics, structure and flow-based ENA indices are each plotted against the degree of centralization determined for each of the 3 urban farm case studies. Although the centralization scores deviate from the expected results, the purpose of the following plots is to examine if a correlation between the degree of agri-network centralization and the ENA metrics can be detected with the networks as constructed. These results are presented here and then discussed in Section 4.4.

The number of actors and links vs. centralization can be found in Figure 24, and the non-dimensional structure-based metrics are found in Figure 25.

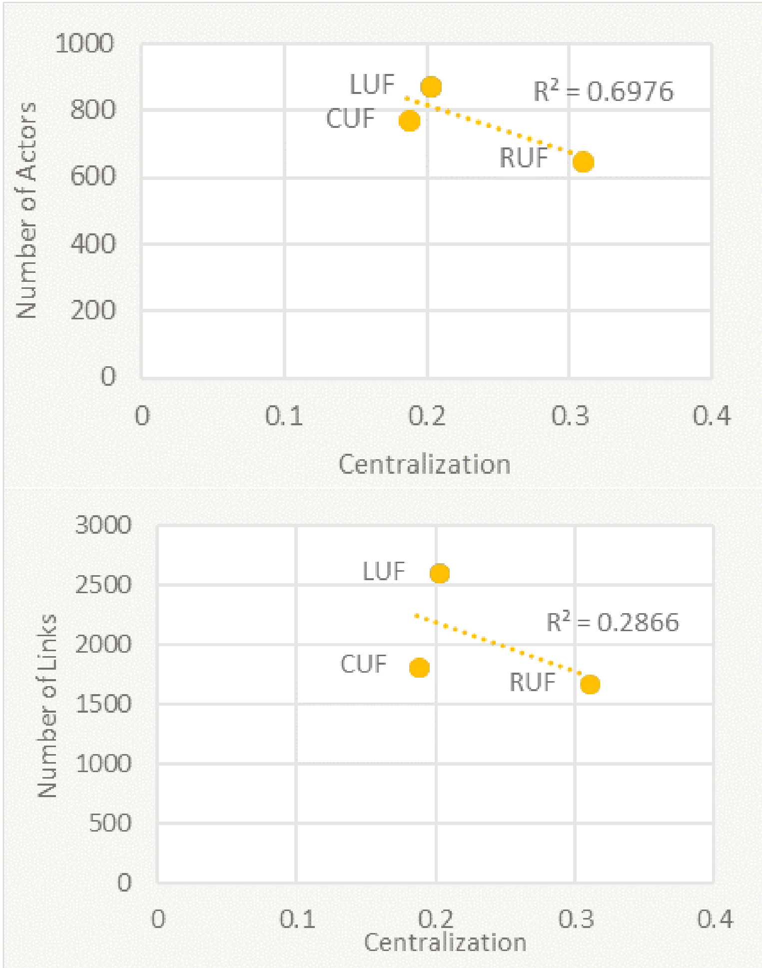


Figure 24: Dimensional ENA structure metrics (number of actors and number of links) for urban farm scenario case studies Zone Urban Farm (ZUF), County Urban Farm (CUF) and Region Urban Farm (RUF) plotted against centralization.

With basin actors, there seems to be no strong correlation between the number of actors or links and the degree of centralization of these networks. These metrics and their potential correlation to level of agri-network centralization are explored in more depth and recalculated without basin actors in Section 4.4.

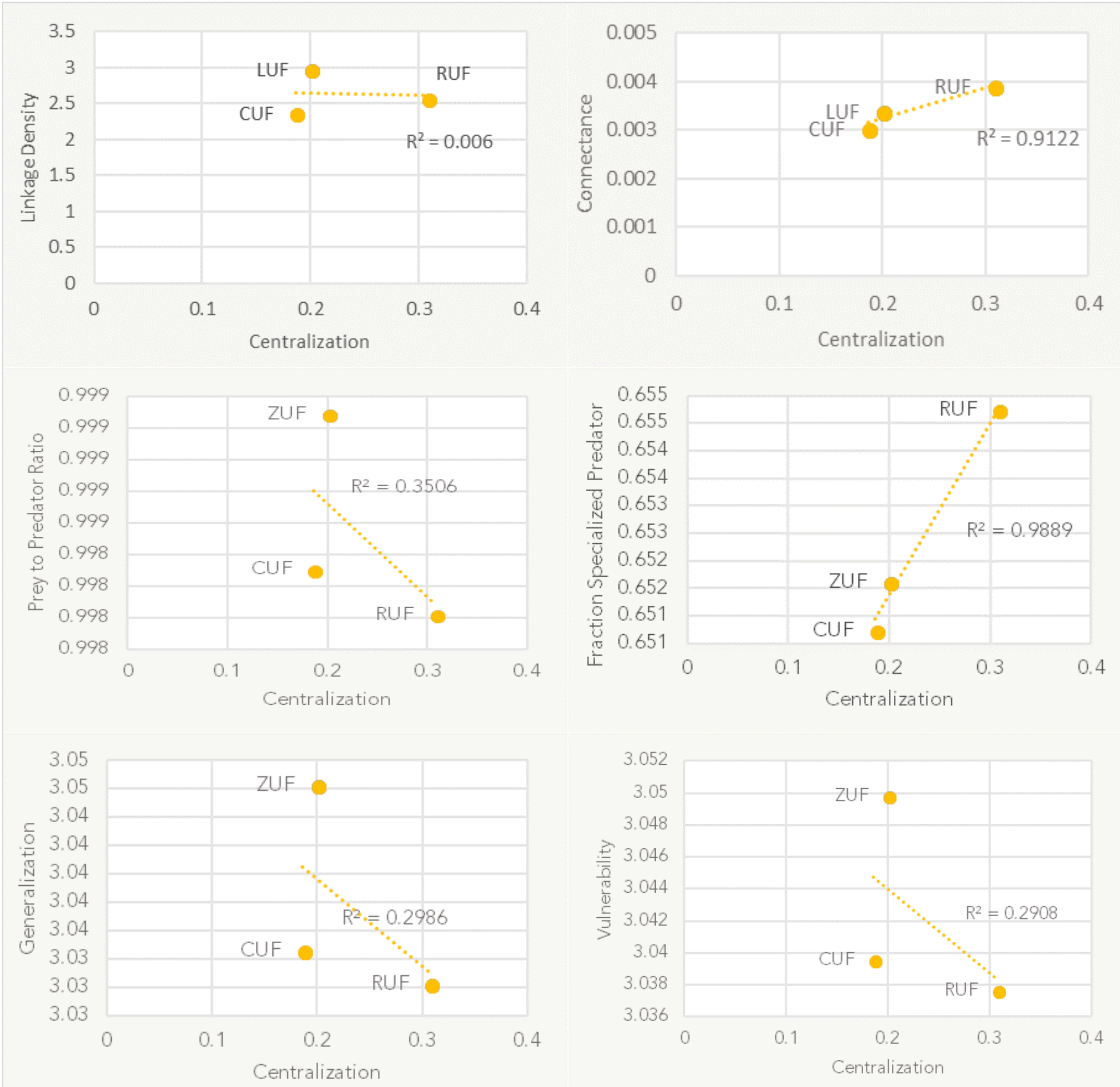


Figure 25: Non-dimensional structure-based ENA metrics for urban farm scenario case studies Zone Urban Farm (ZUF), County Urban Farm (CUF) and Region Urban Farm (RUF) plotted against centralization.

Of the non-dimensional structure-based metrics seen in Figure 25, only connectance and fraction specialized predator have any noteworthy correlation to the centralization metric (with R^2 values over 9) when the networks are analyzed as constructed.

Next, the flow-based metrics are plotted against centralization values for each of the urban farm scenarios. The dimensional metrics, in units of kilograms of nitrogen flow per year, are presented in Figure 26, and non-dimensional flow metrics are presented in Figure 27.

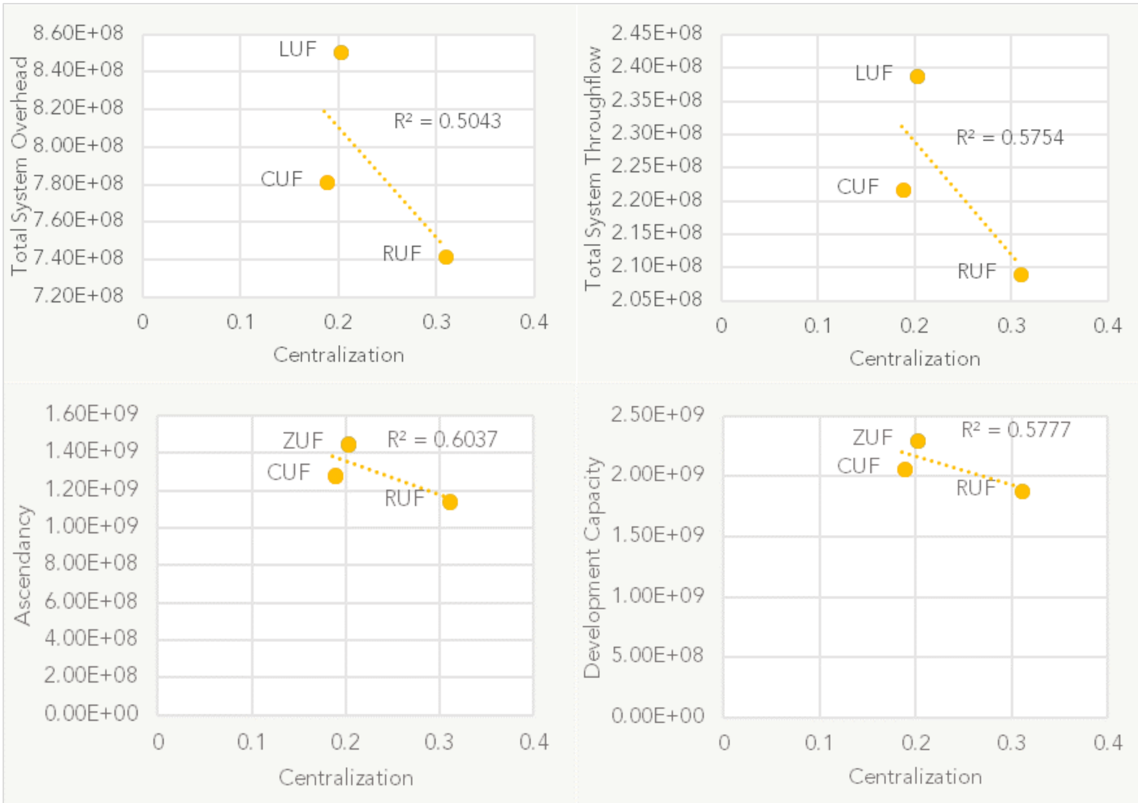


Figure 26: Flow-based metrics, *TSO*, *TST*, *ASC*, and *DC* vs. in units of kg N y^{-1} for urban farm scenario case studies Zone Urban Farm (ZUF), County Urban Farm (CUF) and Region Urban Farm (RUF) plotted against centralization.

There seems to be no strong correlation between the ecological network metrics and the degree of centralization of the networks, when they are analyzed as originally constructed. All of these metrics are explored in more depth in Section 4.4.

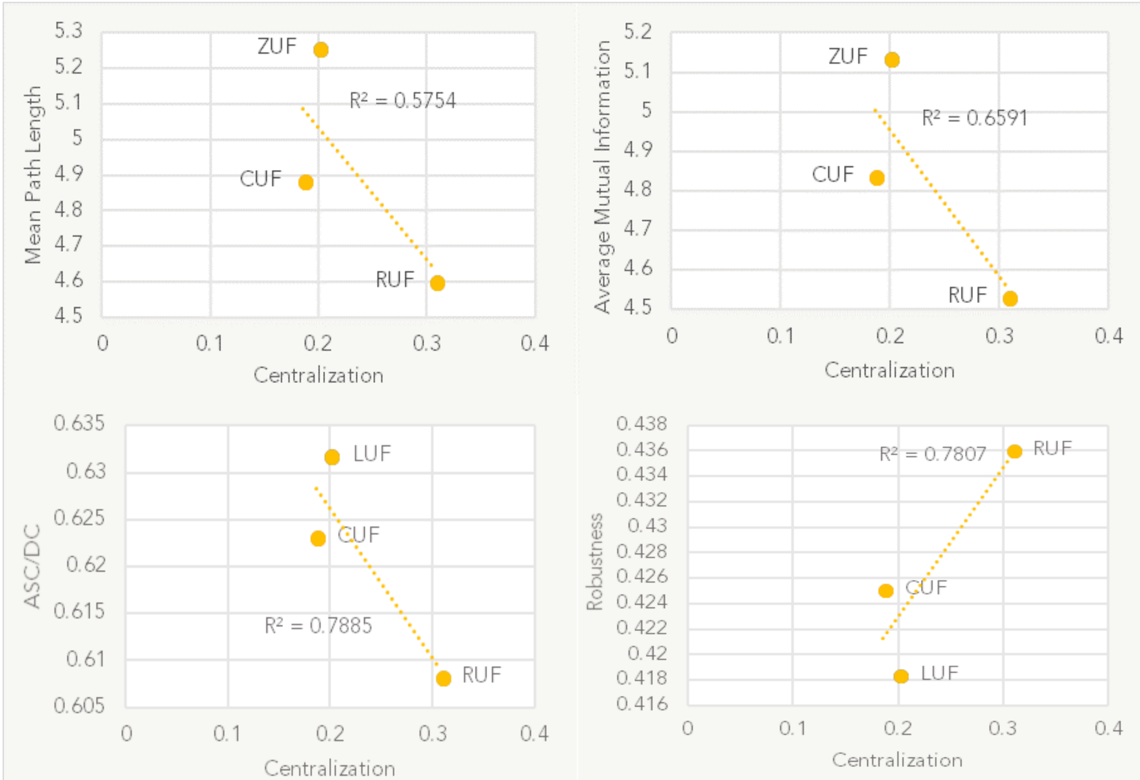


Figure 27: Non-dimensional flow-based ENA metrics for urban farm scenario case studies Zone Urban Farm (ZUF), County Urban Farm (CUF) and Region Urban Farm (RUF) plotted against centralization.

The above figures, Figure 24, Figure 25, Figure 26, and Figure 27 reveal a tenuous correlation between the centralization results and the ENA metrics at best, with 14 of 16 R^2 values under 8. This is determined to be largely due to the inclusion of the basin actors, which serve to skew the centralization results significantly. These results will be discussed in Section 4.4, where the results are re-examined in the context of exclusion of basin actors.

4.3.3 Urban Farm Flows and Impact Results

A Life Cycle Inventory Assessment is conducted on food imports to the baseline and urban farm scenarios. Food miles are estimated for imported foods, and an LCA is conducted to quantify the relative environmental burden incurred by the baseline and the

Urban farm case studies due to food miles. This is done to benchmark if the shift from entirely imported food supply to food grown within the boundary.

The total flow magnitudes of nitrogen imported to the 3 urban farm scenario case studies are reported alongside the internal flows, exports, and dissipation nitrogen flows in Table 12.

Table 12: All 4 case studies' imports, internal flows, exports, and dissipation flow magnitudes (values are given in units of kg N y^{-1}).

Case Study	Imports	Internal Flows	Exports	Dissipation
1 – IE	5.136×10^7	2.037×10^8	7.431×10^6	4.393×10^7
2 – ZUF	4.545×10^7	1.936×10^8	1.525×10^6	4.393×10^7
3 – CUF	4.545×10^7	1.766×10^8	1.525×10^6	4.393×10^7
4 – RUF	4.545×10^7	1.638×10^8	1.525×10^6	4.393×10^7

IE – Import/Export Case

ZUF – Zone Urban Farm Case

CUF – County Urban Farm Case

RUF – Region Urban Farm Case

Imports to the systems include fertilizer, feed, and food. Internal flows result in material changing hands from one actor to another within the system boundary. Exports include only the nitrogen that either has become part of the youth population (assimilated as biomass) or nitrogen that has been taken out of the system as a usable product outside of the defined boundary. This includes land-applied septage or wastewater solids and effluents. Dissipation includes those flows that are unrecoverable wastes, such as those discharged into the receiving water basins or volatilized into atmospheric nitrogen emissions. Only internal flows, those between actors within the boundary, change between the 3 urban farm case studies. These results will be discussed in Section 4.4.

As described in Section 4.2.3, the total amount of food produced in the Region remains constant. These food production totals are presented for each county by category (chicken, produce, and eggs) in Figure 28.

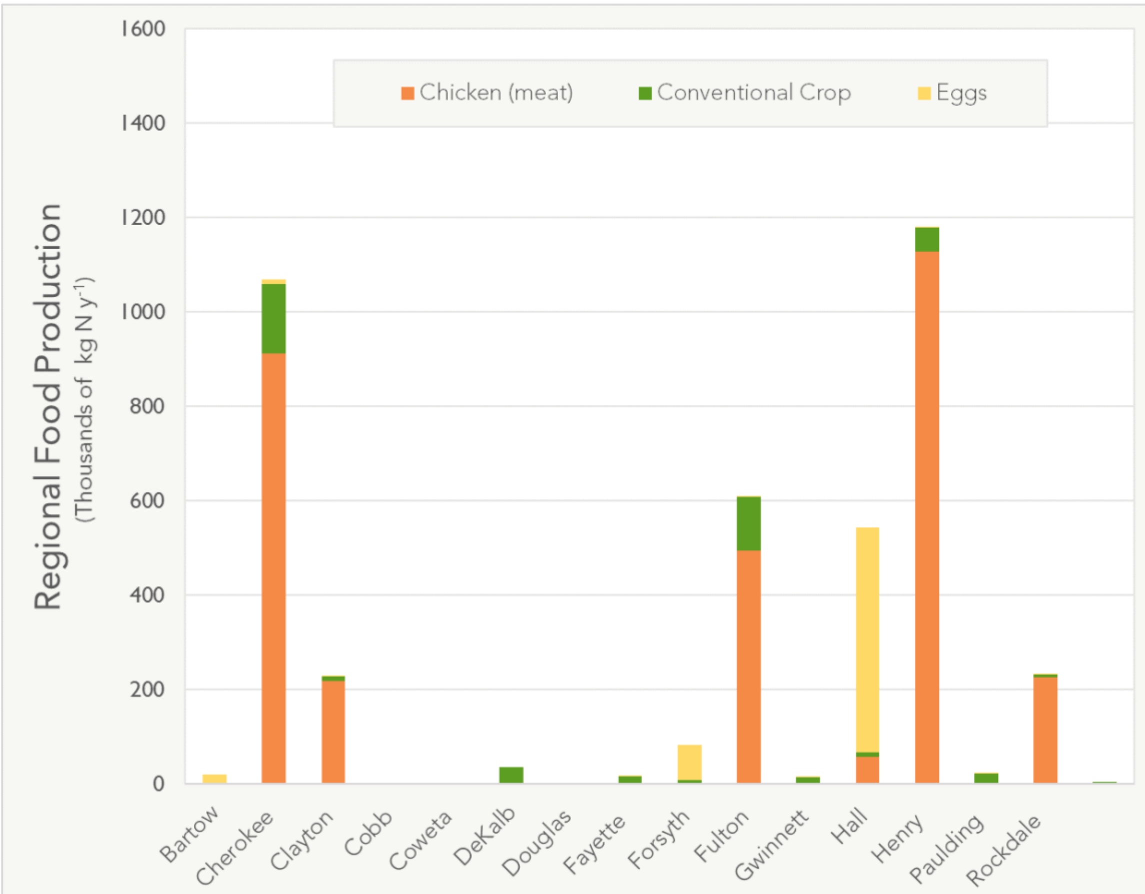


Figure 28: Total nitrogen content of food production in each county, divided by category (poultry meat, crops, and eggs). (Note: these values are held constant in all 4 case studies in the Agri-Network Centralization Experiment (ACE).)

The results from Figure 28 are reported alongside the percentage of total egg, produce, and meat nitrogen requirement for county residents cultivated in each county in Table 13

Table 13: Food production and required by category for each county in the Atlanta Metropolitan Region (USDA 2014).

County	Produced (kg N $^{y-1}$)			Percent of Requirement Met (%)		
	Poultry (meat) N	Crop N	Egg N	Meat N	Produce N	Egg N
Bartow	912,792	146,434	19,527	153.1%	189.8%	69.6%
Cherokee	218,890	8,266	10,913	17.2%	5.0%	18.2%
Clayton	4	1,267	25	0.0%	0.6%	0.0%
Cobb	81	878	341	0.0%	0.2%	0.2%
Coweta	91	35,078	565	0.0%	36.5%	1.6%
DeKalb	0	58	0	0.0%	0.0%	0.0%
Douglas	7	16,142	46	0.0%	15.8%	0.1%
Fayette	14	8,942	89	0.0%	10.9%	0.3%
Forsyth	495,344	113,558	73,058	32.4%	57.4%	101.6%
Fulton	241	14,472	1,496	0.0%	2.0%	0.6%
Gwinnett	57,762	10,195	61	1.2%	1.6%	0.0%
Hall	1,128,439	50,602	475,148	105.5%	36.6%	944.0%
Henry	298	22,565	231	0.0%	14.4%	0.4%
Paulding	225,398	6,883	109	26.6%	6.3%	0.3%
Rockdale	58	3413	291	0.0%	5.2%	1.2%
Total:	**3,039,418**	**438,754**	**581,900**	**10.4%**	**11.6%**	**42.3%**

These results demonstrate that food is disproportionately produced in different areas within the region, with some counties producing over 100% of their need (Bartow, in meat and produce), while others produce none of their requirement (DeKalb has no reported poultry operations nor does it produce a substantial amount of produce.

When summed over the whole region, the total regional imports of eggs, poultry, and produce are reduced by 12% when food is retained within the system boundary. In other words, by keeping food zone in the Atlanta regional food network, the greater Atlanta region area can become 12% more self-sufficient as compared to an Import/Export model. This reduction in imports correlates to a 12% reduction in the food mile impacts brought on by the importation of food products. Because excess food is redistributed within the zones, counties, and regions according to need, the net food imports and farm production remains constant among the 3 urban farm cases.

Using the remainder of food imported to the region in both the baseline and the urban farm cases (which are equal to one another, as mentioned above), an impact assessment is then conducted using the relative food miles required to supply food to the Atlanta Metropolitan Region population for each scenario. The values of the top 5 food producers, which are ranked by their out-strength and their relative proportions of the total magnitude of node out-strength are used to determine food miles traveled and proportion of imported food to the region (see Section 4.2.5.2).

The Impact Characterization can be found for the urban farm scenario (which includes ZUF, CUF, and RUF) and the baseline (IE) in Table 14.

Table 14: Life Cycle Impact Characterization for food miles in the Baseline as compared to the Urban Farm Scenario.

Impact category	Unit	Baseline (Import/Export)	Urban Farm Scenario
Global warming, Human health	DALY	1482.4	1334.2
Global warming, Terrestrial ecosystems	species.yr	4.473	4.026

Table 14 (Continued)

Global warming, Freshwater ecosystems	species.yr	1.22E-04	0.000
Stratospheric ozone depletion	DALY	5.66E-01	0.509
Ozone formation, Human health	DALY	4.18	3.76
Fine particulate matter formation	DALY	1080	970
Ozone formation, Terrestrial ecosystems	species.yr	0.61	0.55
Terrestrial acidification	species.yr	0.74	0.66
Freshwater eutrophication	species.yr	0.24	0.21
Terrestrial ecotoxicity	species.yr	0.172	0.155
Freshwater ecotoxicity	species.yr	0.015	0.013
Marine ecotoxicity	species.yr	0.004	0.003
Human carcinogenic toxicity	DALY	171.86	154.67
Human non-carcinogenic toxicity	DALY	188.735	169.862
Land use	species.yr	0.967	0.870
Mineral resource scarcity	USD2013	674700	607200
Fossil resource scarcity	USD2013	210,646,300	189,581,700
Water consumption, Human health	DALY	21.62	19.46
Water consumption, Terrestrial ecosystem	species.yr	0.13	0.12
Water consumption, Aquatic ecosystems	species.yr	5.88E-06	0.000

The largest contributors to the environmental burden of food miles can be seen in fossil resource scarcity, on account of the fuel consumption, which is measured in dollars. The results of the LCA indicate that over $21 Million each year could be save on account of this change to fossil resource usage if this portion of food was sourced from within the boundary. Similarly, the global warming impacts to human health, which are measured in DALYs (disability-adjusted life years) are another large impact characterization area for food miles. DALYs are derived from human health statistics on life years lost or spent disabled (Goedkoop, Heijungs et al. 2009). This is likely resulting from the use of energy and fossil fuels for climate-controlled transport of food products.

4.4 Discussion

The results presented in Section 4.3 are discussed in the following sections. First, the networks as originally constructed are compared to one another and benchmarked using natural ecosystem median metric values drawn from literature in Section 4.4.1 (Borrett Stuart and Lau Matthew 2014, Layton 2014). Next, noting the skewed centralization results mentioned in Section 4.3.2, the networks are modified to remove the basin actors, and centralization and network analysis results are recalculated, and these new results are presented and discussed in Section 4.4.2. Building on this discussion, Section 4.4.2. also explores actor designation and aggregation in order to call attention to the impacts these choices can have on ecological network analysis results and inform future applications of ecological network analysis as a sustainable systems design tool.

4.4.1 Natural Ecosystem Benchmarks and Comparison of Case Studies

Ecological network analysis (ENA), when applied to human systems, enables designers and engineers to compare these human systems to one another and to evaluate them alongside natural ecosystems to determine how they perform within an ecological context. In the following section, the 4 evaluated case studies are compared against natural food web median values drawn from literature in a series of graphs (Odum 1969, Borrett Stuart and Lau Matthew 2014, Layton 2014).

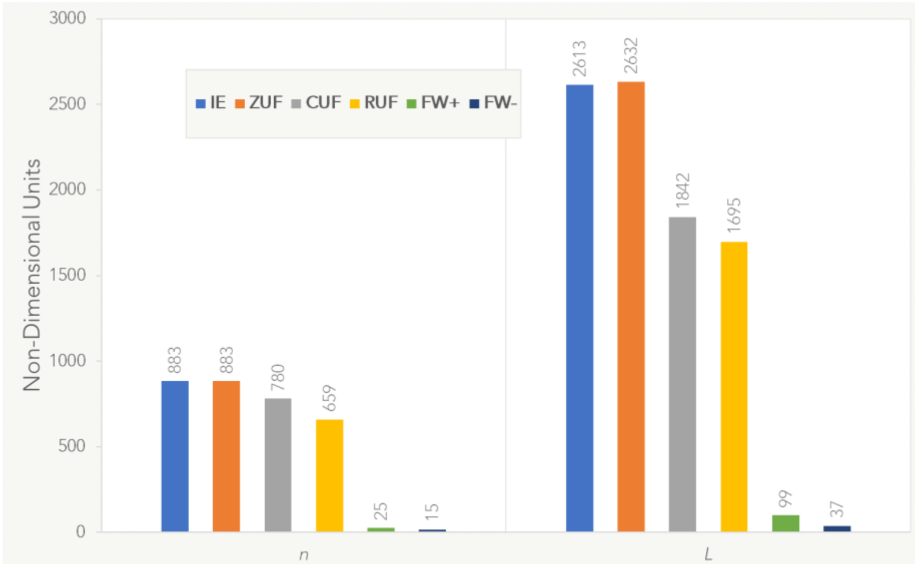
Table 15, 

Figure **29**, Figure 30, and Figure 31 present side-by-side comparisons of structure metrics for the 4 Agri-Network Centralization Experiment (ACE) case studies and median values for food webs with and without detritus actors (Borrett Stuart and Lau Matthew 2014, Layton 2014). Metrics pictured include: Species Richness (n), Number of Links (L), Linkage Density (L_D), Prey-Predator Ratio (P_R), Fraction Specialized Predator (P_S), Generalization (G), Vulnerability (V), And Cyclicity (λ_{max}). As described in Chapter 3, some of these metrics are dimensional metrics (n, L, n_{prey}, $n_{predator}$, $n_{s\text{-}predator}$), all of which describe the number of actors or links in the system, while some of the metrics are dimensionless (such as L_D, C, G, V, P_R, P_s, and λ_{max}).

Table 15: ENA structure metric results for all 4 case studies and food (Borrett Stuart and Lau Matthew 2014, Layton 2014).

Case Study	n	L	L_D	C	n_{Prey}	$n_{Predator}$	P_R	λ_{max}	$n_{s\text{-}predator}$	P_s	V	G
1 – IE	883	2613	1.68	0.003	880	881	0.999	0	654	0.75	2.68	2.68
2 - ZUF	883	2632	2.981	0.003	863	864	0.999	0	563	0.652	3.05	3.05

3 - CUF	780	1842	2.362	0.003	606	607	0.998	0	395	0.651	3.04	3.03
4 - RUF	659	1695	2.572	0.004	558	559	0.998	0	366	0.655	3.04	3.03
FW+	25	99	3.91	0.19	25	21	3	1.11	0.086	6.18	5.34	4.24
FW-	15	37	1.96	0.13	13	13	4	1.06	0.139	2.33	2.43	1

IE – Import/Export Case
ZUF – Zone Urban Farm Case
CUF – County Urban Farm Case
RUF – Region Urban Farm Case
FW+ – Post 1993 food webs (with detritus actors)
FW- – Pre-1993 food webs (without detritus actors)

n – number of species (species richness)
L – number of links

C – Connectance
n_{prey} – Number of Prey
$n_{predator}$ – Number of Predators
$n_{s\text{-}predator}$ – Number of Specialized Predators
P_R – Prey to Predator ratio
λ_{max} – Cyclicity
P_s – Fraction Specialized Predators
V – Vulnerability
G – Generalization

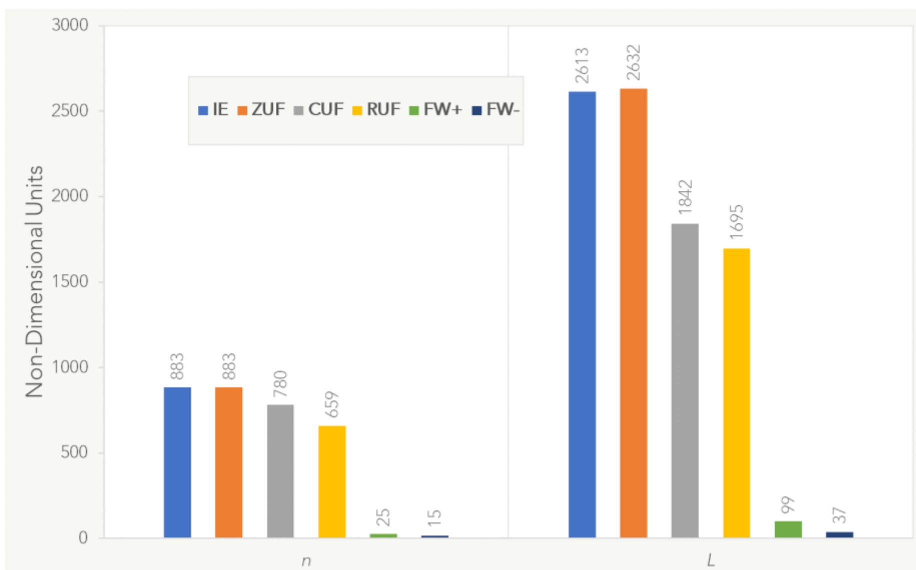


Figure 29: Number of actors and links in the 4 ACE case studies compared to natural food webs (FW) with and without detritus actors (FW+, with detrital actors; FW-, without detrital actors) (Borrett Stuart and Lau Matthew 2014, Layton 2014).

From Figure 29 it can be seen that there are large differences in the size between the food web medians and the 4 case studies evaluated in the Agri-Network Centralization

Experiment (ACE) and the natural food webs. Accordingly, the Number of Prey (n_{prey}), Predators ($n_{predator}$), and Specialized Predators ($n_{s\text{-}predator}$) vary by similar degrees, so they are not pictured here. Several structure metrics depend directly on species richness (e.g. linkage density and connectance). This difference from natural food web data is an artefact of the difference in network size and may not be significant. However, it may indicate that there is a difference in the degree of aggregation occurring in the ACE networks and those in the ecological literature, which will be explored at much greater depth in Section 4.4.2.

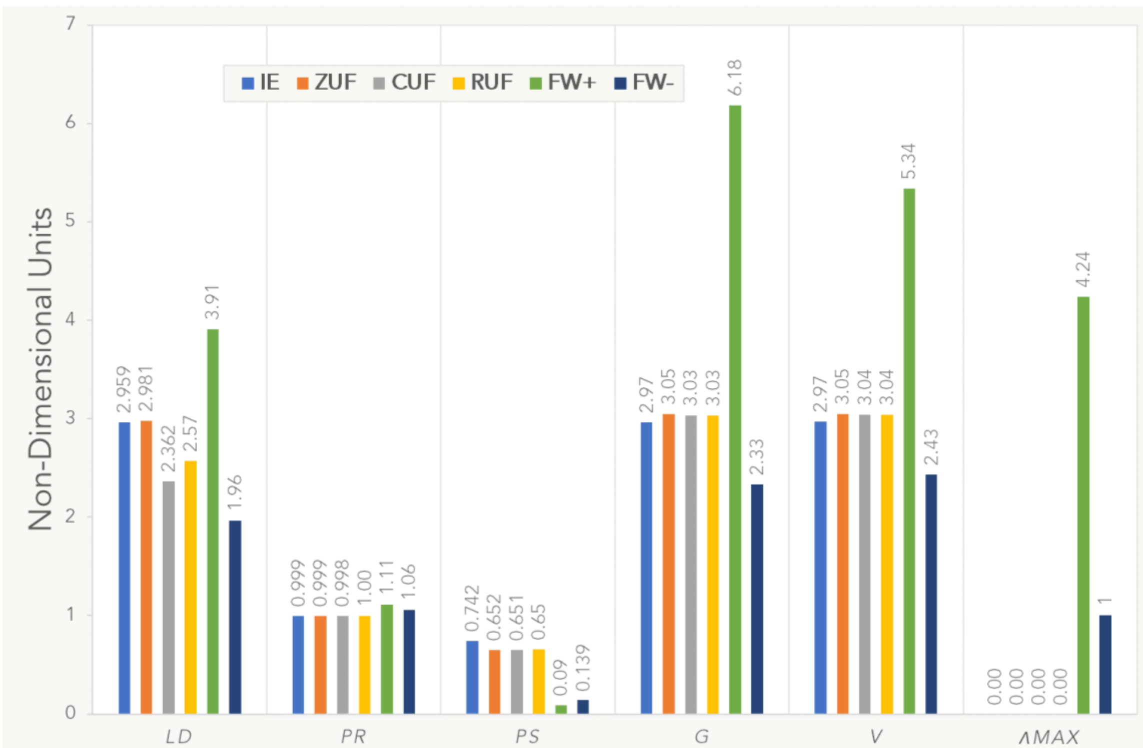


Figure 30: Structure metrics for ACE case studies and natural food web (FW) medians with detrital actors (+) and without (-). Metrics include: Linkage Density (L_D), Prey-Predator Ratio (P_R), Fraction Specialized Predator (P_S), Generalization (G), Vulnerability (V), And Cyclicity (λ_{max}) (Borrett Stuart and Lau Matthew 2014, Layton 2014).

From Figure 30 it can be seen that most of the metric values differ by a large margin from the post-1993 food web medians. However, some of the metric values of the ACE case studies are close to, or in some cases better than, the values found for the food webs prior to 1993, before detritus actors were incorporated into the food webs. For example, all of the ACE case studies' prey-predator ratios are 6% lower than the pre-1993 food web. Additionally, all 4 case studies evaluated in the ACE have higher linkage densities (20%, 31%, 51%, and 52% for CUF, RUF, IE, and ZUF, respectively) than the pre-1993 food webs. Accordingly, the ACE case studies also have higher Vulnerability (22-25%) and Generalization (27-31%) metric results than the early food web models, which indicates that each predator in the ACE case studies derives material inputs from more "prey," and each "prey" provides material to more "predators," than in these early food web representations.

When the natural food webs were revisited in the early 1990s, ecologists created much more complex representations of these networks. The median values calculated for these newer, more accurate food web models more starkly contrast the ACE case studies. Indeed, the deficit of prey per predator increases to 10% when compared to the median post-1993 food web value. This prey-predator ratio less than one indicates that all 4 case studies also possess more predators than prey, which means that each actor in the ACE case studies transfers material to fewer other actors than in natural food webs. This means that there is more competition for resources in the ACE case studies than in nature. Their linkage densities are also significantly reduced from the post-1993 natural food web medians (24%, 24%, 30%, and 40% for IE, ZUF, RUF, and CUF, respectively), meaning that the actors in the ACE case studies interact with far fewer other actors in their networks than the actors in natural food webs.

Accordingly, the ACE values are significantly lower than the median Generalization and Vulnerability results of the improved food webs (51-52% and 43-44% reductions, respectively), indicating that the actors in the ACE case studies are more specialized than in most food webs when detritivores are included. This can be seen most prevalently in the Zone Urban Farm Case, where farms predominantly provide crop to zone groceries and subsequently to zone populations. This is a simplification that is a relic of the design of the networks. In a real urban food network, populations within a given zone may travel outside of their zone to purchase groceries, and there would likely be much more linkage diversity between populations and restaurants, as well. In a more complex model, the links between restaurants, groceries, and populations would not be confined within the zone, which would lead to generalization values being reduced from their present values. Likewise, restaurants and groceries would be visited by populations outside of their zone, and the vulnerability value would likely go down as well.

This highly selective, specialized interactivity between actors in the ACE case studies becomes further evidenced by their Connectance (*C*) values. These values for the 4 ACE case studies are plotted next to the median connectance values for natural food webs with and without detritus actors drawn from literature in Figure 31 (Borrett Stuart and Lau Matthew 2014, Layton 2014).

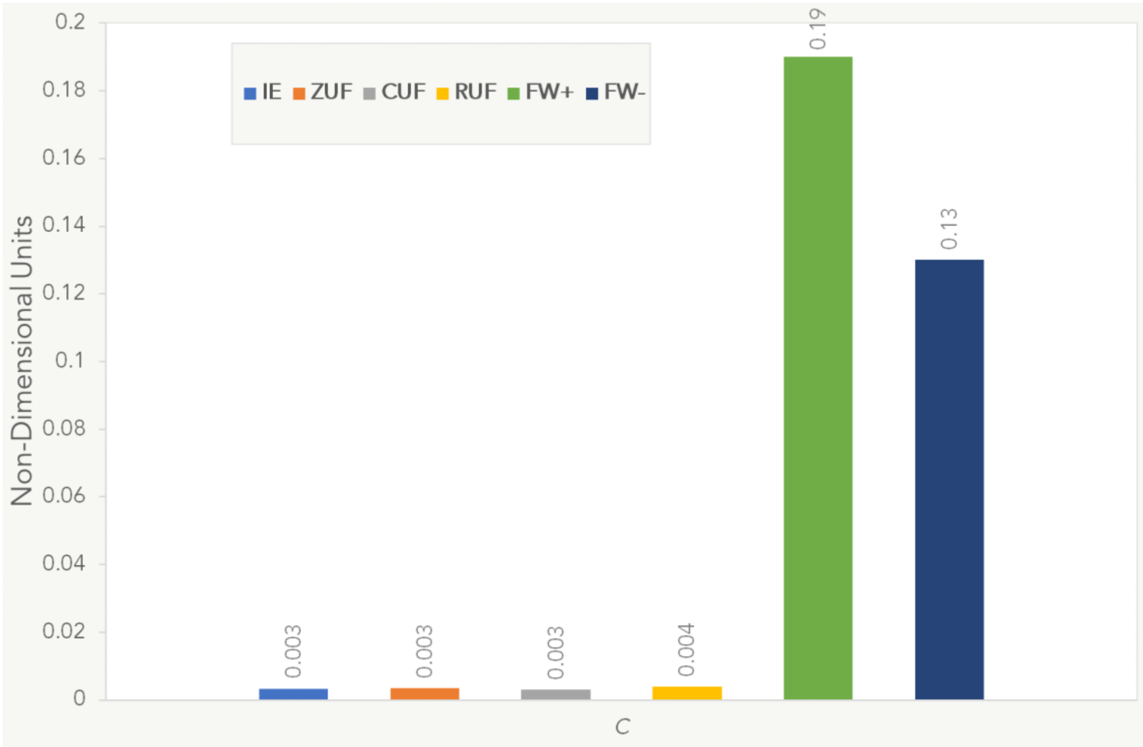


Figure 31: Connectance (*C*) values of ACE case studies compared to natural food web (FW) medians with detrital actors (+) and without (-). FW values drawn from (Borrett Stuart and Lau Matthew 2014, Layton 2014).

As can be seen, the Connectance in the ACE case studies is nearly two orders of magnitude from both of the food web medians. This means that each of the representations of the Atlanta Metropolitan Region food network are constructed in such a way in this study that the percentage of actual links out of the total possible links is significantly smaller than natural systems.

In order to compare more closely between the 4 case studies, the food web median is removed in Figure 32.

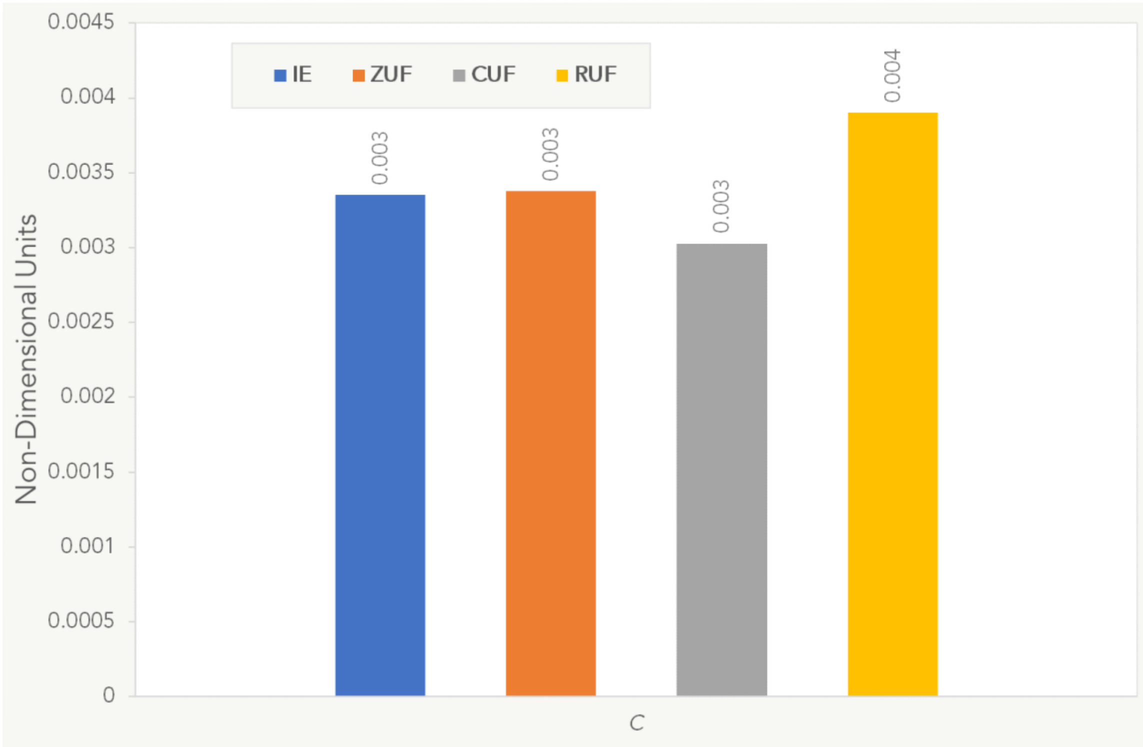


Figure 32: Connectance values plotted for all 4 ACE case studies.

The change between the first and second case studies, Import/Export (IE) and Zone Urban Farm (ZUF) can be attributed to the links that are added between farm and food distribution actors in the ZUF configuration. Additionally, it can be seen that the most centralized case study from the urban farm scenario, Region Urban Farm (RUF) has improved connectance value over the other case studies. RUF shows an increase (29%) over the lowest connectance value, that of the County Urban Farm (CUF) network and an increase (16%) over the next highest value, which belongs to the Zone Urban Farm (ZUF) case.

This finding suggests that the more centralized urban food network, as constructed, leverages a higher percentage of its possible links. However, the RUF network also has the fewest actors, which means that it contains fewer possible links. Conversely, the ZUF network, even with its increase in species richness, still has a higher connectance than the CUF network. This may seem like a surprising result, but the lower connectance in the CUF case likely has to do with the fact that the number of links added from ZUF (case 2) to CUF (case 3), as it compares to the added species richness, is much more drastic than the change from CUF to RUF (case 4). When the zone farm actors are removed, there are 790 links and only 103 actors removed, whereas when the county farms are removed from CUF to RUF, 121 actors are removed and only 147 links are removed.

Following comparison of the structure metrics, the flow-based metrics are compared in Table 16.

Table 16: ENA flow-based metrics for all 4 case studies alongside food web median values for post-1993 food webs (Borrett Stuart and Lau Matthew 2014, Layton 2014).

Case Study	*FCI*	*MPL*	*AMI*	*ASC*	*DC*	*TSO*	*TST*	*ASC/DC*	*R*
1 - IE	0	4.97	5.11	$1.57x10^9$	$2.46x10^9$	$8.96x10^8$	$2.55x10^8$	0.64	0.42
2 - ZUF	0	5.26	5.14	$1.46x10^9$	$2.31x10^9$	$8.52x10^8$	$2.39x10^8$	0.63	0.42
3 - CUF	0	4.89	4.84	$1.29x10^9$	$2.08x10^9$	$7.83x10^8$	$2.22x10^8$	0.62	0.43
4 - RUF	0	4.60	4.53	$1.15x10^9$	$1.90x10^9$	$7.42x10^8$	$2.09x10^8$	0.61	0.44
FW+	0.295	5.7	1.68	18100	39500	20700		0.372	0.524

IE – Import/Export Case

ZUF – Zone Urban Farm Case

CUF – County Urban Farm Case

RUF – Region Urban Farm Case

FW+ – Food web median values (with detrital actors)

FCI – Finn's Cycling Index

MPL – mean path length

AMI – average mutual information

DC – development capacity

TSO – total system overhead

TST – total system throughflow

R - robustness

The non-dimensional flow-based metrics are compared for the 4 case studies and the post-1993 food web medians, which can be seen in Figure 33.

Figure 33: Non-dimensional flow metrics for the 4 ACE case studies (Import/Export (IE), Zone Urban Farm (ZUF), County Urban Farm (CUF), and Region Urban Farm (RUF)) compared to post-1993 food web medians (FW+) (Borrett Stuart and Lau Matthew 2014, Layton 2014).

Figure 33 clearly demonstrates that there is no cycling present in the ACE case studies as constructed. This is likely under-representative of the nitrogen cycling due to the simplifying assumptions made regarding overall network connectivity, composting, and agriculture practices in the region (discussed in more depth in Section 4.4.3).

The Mean Path Length (*MPL*) of the 4 ACE case studies is also deficient as compared to the natural food web median, which can likely be attributed to the simplified network complexity used to model the Atlanta Metropolitan Region's food system. The Region Urban Farm case shows the worst of all the MPL values, with a 25% reduction from the food web median. The highest *MPL* is exhibited by the Zone Urban Farm (ZUF) case study, which makes sense given the extension of the fertilizer and feed distribution hierarchies down to the zone level, and the added levels of finished farm product distribution actors that convey material back up the geographic hierarchy.

A more realistic network is likely far more reticulated, with materials changing hands in more complicated ways than the model depicts (Ulanowicz 2009). For example, in reality, multiple feed suppliers likely compete for poultry farmers' business, different logistics companies cover different areas within the region, and population actors go to many different restaurants within and outside of the region.

Conversely, the Average Mutual Information (*AMI*) values for all of the ACE case studies is well above the *AMI* median for natural food webs. Once again, the RUF case shows the lowest value of the ACE case studies, with a 172% increase over the food web median, while the ZUF case has the highest *AMI* value, with a 204% increase over the food web median. This drastic increase in *AMI* as compared to the food web medians is likely due to the level of detail used to articulate the actors in this experiment as compared to the trophic aggregation that occurs in ecological studies. Aggregation has been shown to decrease network Ascendancy (*ASC*), and by extension *AMI*, as the removal of weaker connections within a network and absorption of smaller actors into larger aggregates tends to lead to reduced flow path constraints and increase the number of parallel pathways in the system (Ulanowicz and Kemp 1979, Allesina, Bodini et al. 2005). The higher *AMI* in the ACE cases is to blame for their relative increase in *ASC/DC* and decrease in Robustness (*R*) These concepts will be explored in much greater depth in Section 4.4.2.

4.4.2 Actor Definition, Aggregation, and System Constraints

As noted in Section 4.3, the results of the agri-network centralization experiment are significantly skewed from the originally-intended network centralization scale, in which Zone Urban Farms represented the least centralized production strategy, followed by County Urban Farms, with Region Urban Farms representing the most centralized food production strategy. In order to test whether the basin actors are to blame for this discrepancy, the basin actors are removed from all 4 case studies and their centralization and ecological network indices are recalculated and discussed in Section 4.4.2.1. Next, Section 4.4.2.2 explores the impacts actor definition can have on ecological network indices in order to inform future efforts to leverage ENA as an urban food system design tool.

4.4.2.1 <u>Basin Actors and the "Centralization Effect"</u>

Inclusion of the water basins as network actors added several complicating factors. Initially, this became evident in the calculation of the centralization metric. Figure 34 illustrates a "centralization effect" wrought by inclusion of the Chattahoochee and Coosa actors in the food network for Fulton County.

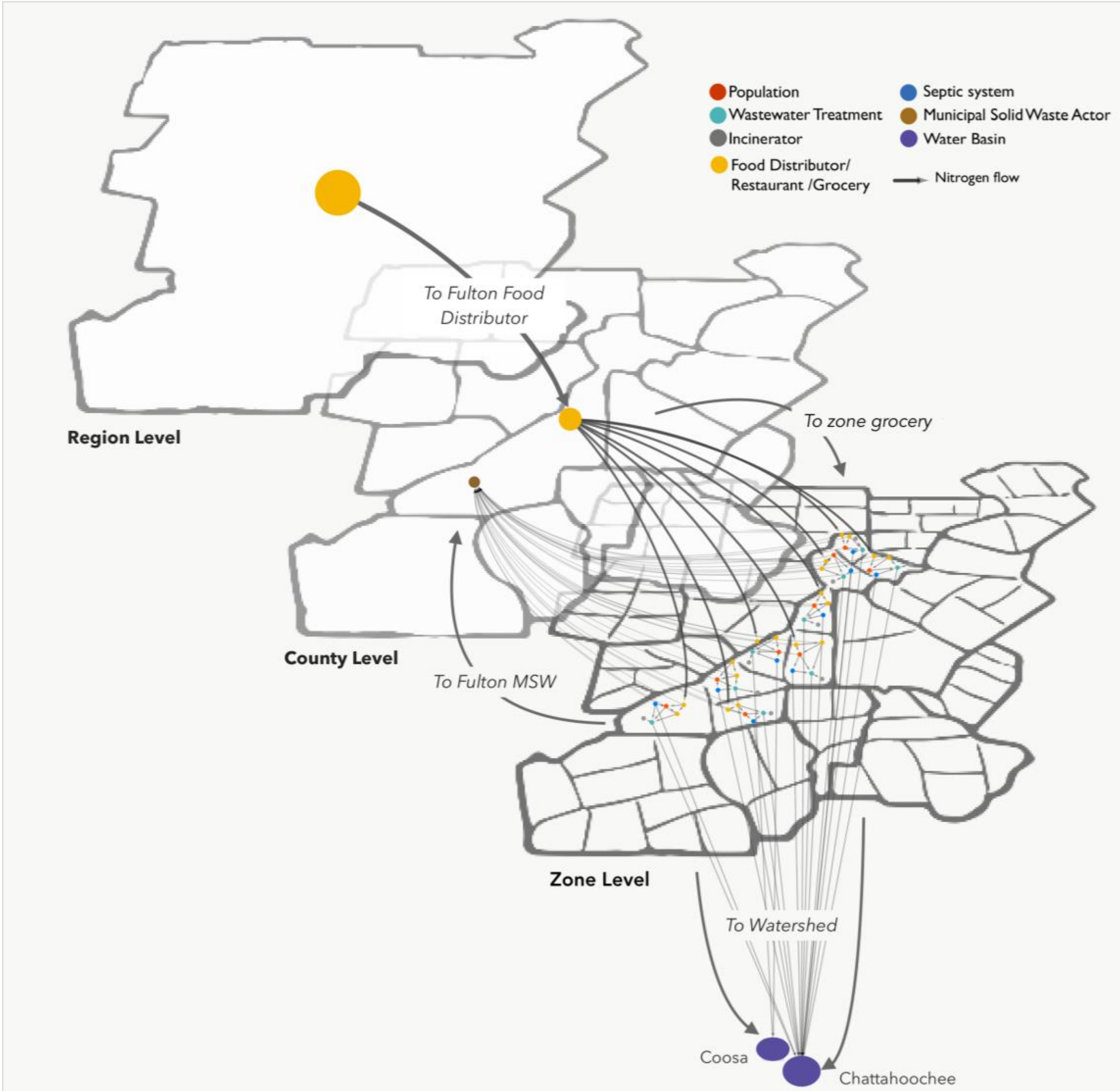


Figure 34: Food distribution and waste pathways for Fulton County. Purple actors represent Water Basin actors, Chattahoochee and Coosa.

As can be seen in Figure 34 above, the Basin actors, especially Chattahoochee, has a high degree of connectivity. Upon closer inspection, it can be seen that this actor has as high a degree (16 with Fulton County's zones) as any other actor elsewhere in the network (the next-highest are the Region-level distribution actors, each with between 15-18 connections). Recall, the centralization metric used in this study, as described in Section 3.2, is a structure-based metric. It looks at the degree of connectivity of each node, meaning how many structural connections are present. This centralization metric is dependent on number of connections to any given node, and does vary depending on the weight of each of the node's connections. If we revisit the equation for Centralization (C_N), first introduced in Section 3.2, we can see that the presence of these strongly-connected basin actors significantly complicates the centralization concept:

$$C_N = \frac{\sum_{i=1}^{N} k_x(v_*) - k_x(v_i)}{max \sum_{i=1}^{N} k_x(v_*) - k_x(v_i)} \tag{31}$$

where $k_x(v_i)$ is the connectivity measure of point i and $k_x(v_*)$ is the largest connectivity measure in the network (Freeman 1978, Dong and Horvath 2007). In other words, the centralization results found for the case studies with basins actors, reported in Section 4.3.2, does not accurately reflect the levels of "Agri-Network Centralization" intended with the networks' design. With this in mind, the basin actors were removed from each of the 4 networks, and their inputs were sent straight to dissipation in the ENA flow matrix.

The case studies are then re-analysed with respect to centralization. These results are illustrated in Figure 35 alongside the original Centralization results.

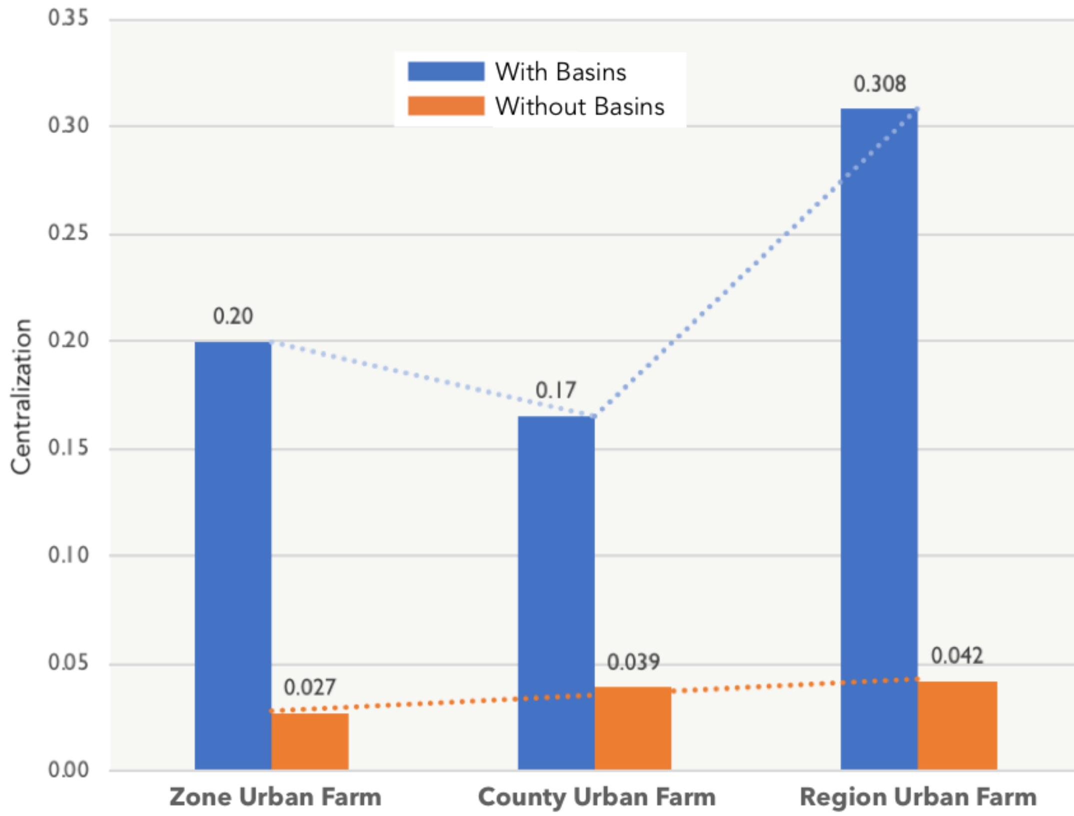


Figure 35: Network centralization scores of urban farm case studies with and without Basin actors for Zone Urban Farm (ZUF – case 2), County Urban Farm (CUF – case 3), and Region Urban Farm (RUF – case 4).

In blue, when basins are included, the basin actors serve to connect some of the smaller zone-level flows, making the networks appear to be more centralized than the orange results, when basins are removed from the models. This is especially evident in the Region Urban Farm (RUF – case 4), where all the flows from farms go directly to the Chattahoochee Basin. The results also suggest that by defining the basins as individual actors, the relative degree the case studies' Centralization is out of order, with the County Urban Farm (CUF – case study 3) appearing to be less centralized than the Zone Urban Farm (ZUF – case 2). This can be attributed to the presence of over 170 zone farms in ZUF with all of their connections to the basin actors, bringing the ZUF centralization score up above that of CUF. Without the basin actors, however, the relative level of centralization of the Agri-Networks becomes much more aligned with their intended designs.

This becomes clearer by presenting their network diagrams using a “prefuse force-directed” layout. This kind of network visualization uses a class of algorithms that positions nodes so that all the edges are spread out in such a way as to have as few crossings as possible. The length of the edges seen here correlate to the relative “weight” of the edge. In other words, longer edges correspond to higher magnitudes of material movement (nitrogen) from central importers to zones, populating the outer reaches of the network. Figure 36 presents the 4 case studies visualized in this way.

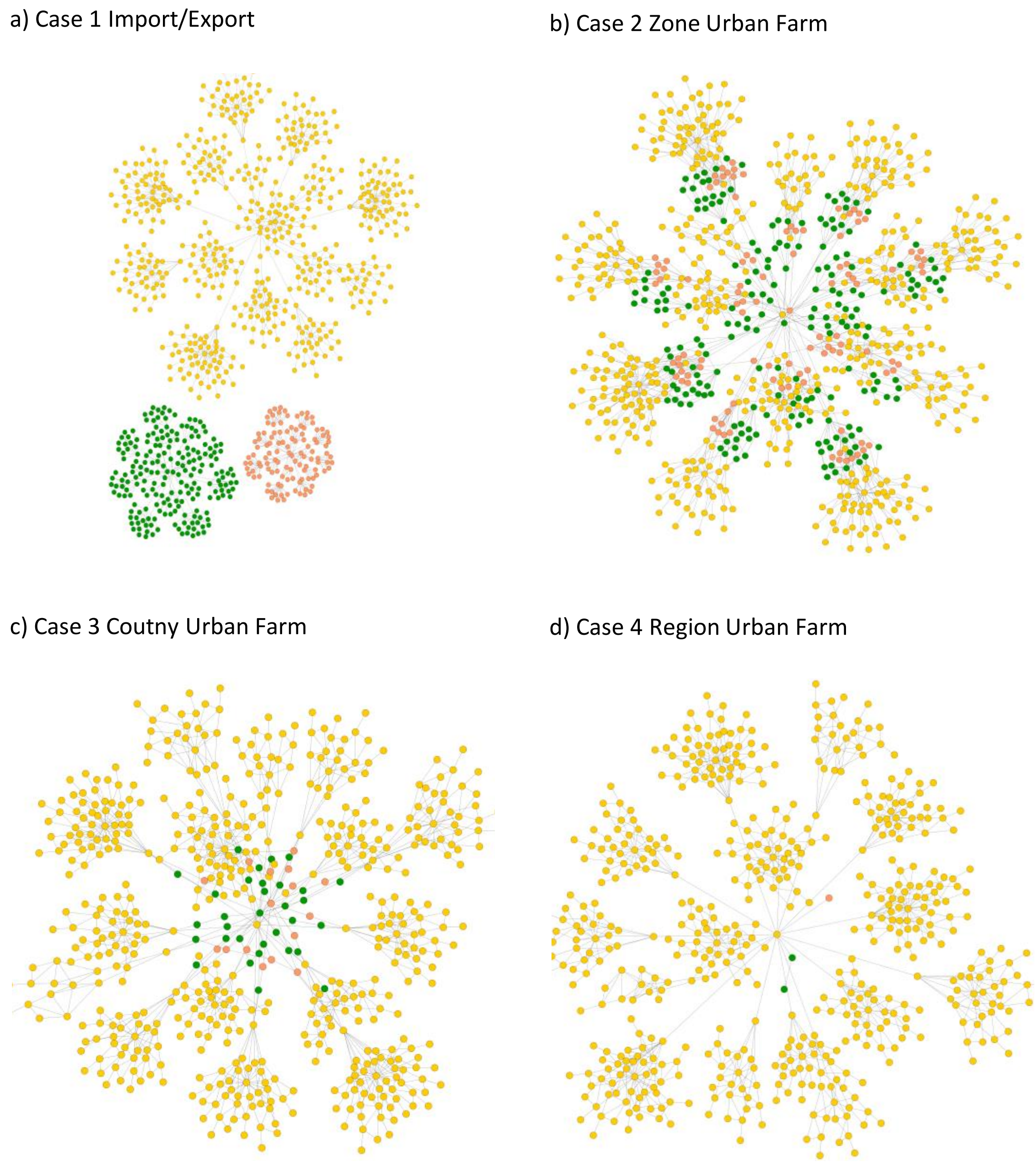


Figure 36: Force-directed network graphs for all 4 case studies in the Agri-Network Centralization Experiment. Food, population, and waste actors (yellow), Crop industry actors (green), and poultry industry actors (orange) show relative degree of centralization of the Agri-Networks.

When the 4 case studies are visualized in this manner, the dispersal of farm actors out from the center towards the outer network nodes becomes much more apparent.

With the basin actors now removed, the case studies are reanalysed using methods described in Sections 3.1 and 4.2.5. Then the ecological network metrics for the urban farm networks are once again compared with respect to network centralization.

The structure metric comparisons can be found in Figure 37 and Figure 38.

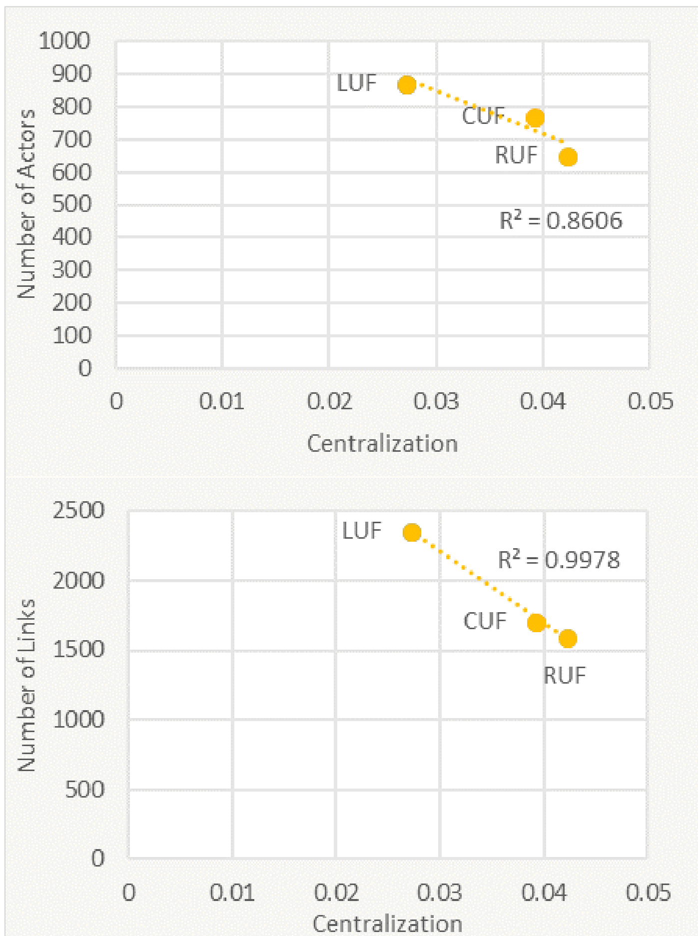


Figure 37: Dimensional structure metrics for the 3 urban farm case studies with basins removed. Zone Urban Farm (ZUF – case 2) is the least centralized case,

followed by County Urban Farm (CUF – case 3), and finally Region Urban Farm (RUF – case 4) is the most centralized urban agri-network.

When compared with the original ENA-centralization plots presented in Figure 24 on page 123, it can be seen from Figure 37 with the modified networks that the correlation between dimensional structure metrics and centralization improves when basin actors are removed. This is especially apparent in the number of links, where the original root-squared value was below 7, whereas the new metric correlation has a very close to linear relationship. The number of actors also more closely follows a linear trend here, improving from an R^2 of 0.69 to 0.86.

The non-dimensional structure metrics are plotted against centralization in Figure 38.

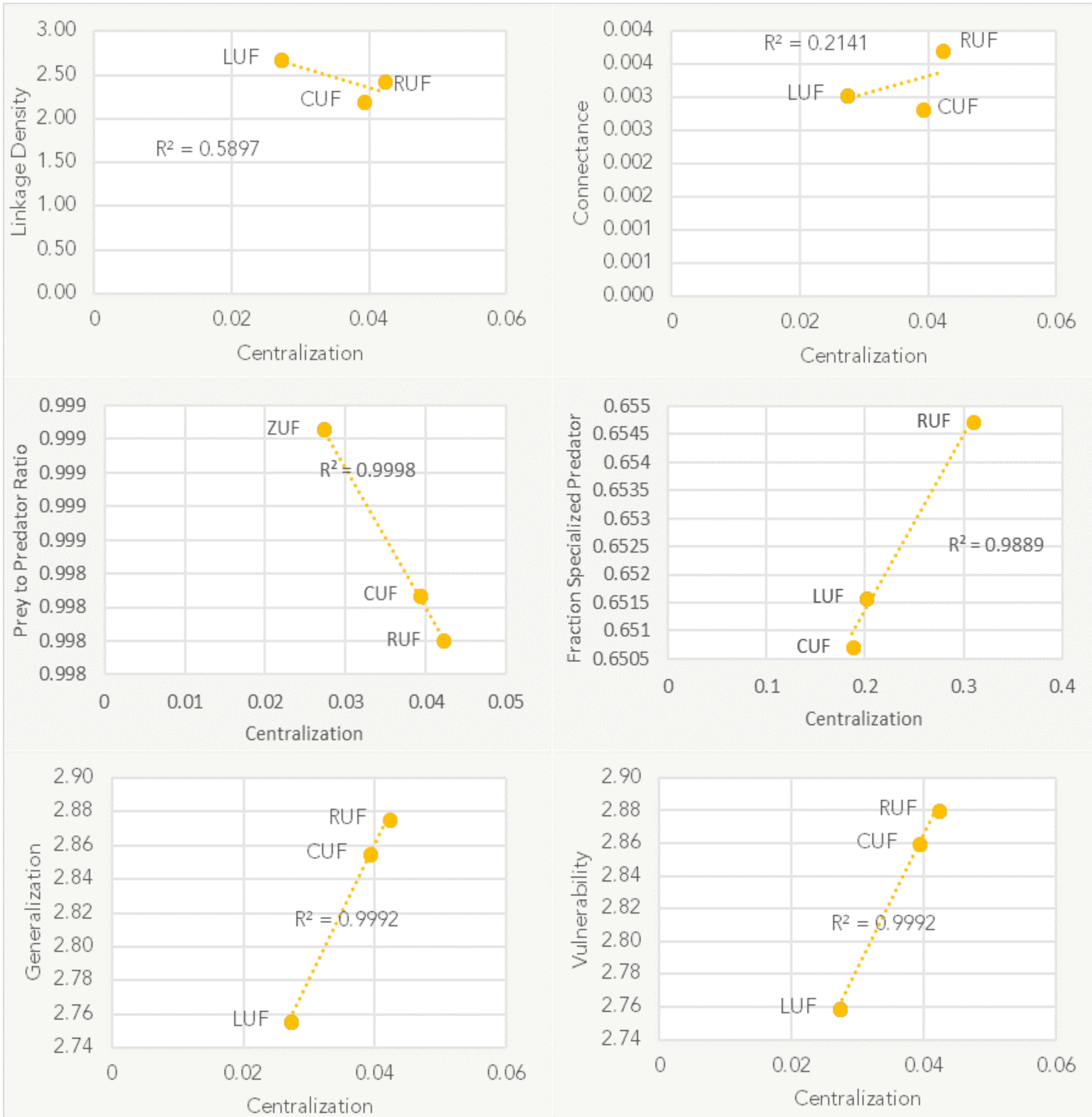


Figure 38: Non-dimensional structure metrics plotted versus centralization for the 3 urban farm case studies without basins. Zone Urban Farm (ZUF – case 2) is the least centralized case, followed by County Urban Farm (CUF – case 3), and finally Region Urban Farm (RUF – case 4) is the most centralized urban agri-network.

Flow metrics are also replotted with respect to network centralization for the modified networks with their basins removed. The non-dimensional flow metrics, including Mean Path Length (MPL), Average Mutual Information (AMI), Ascendancy over Development Capacity (ASC/DC), and Robustness (R) can be found in Figure 39.

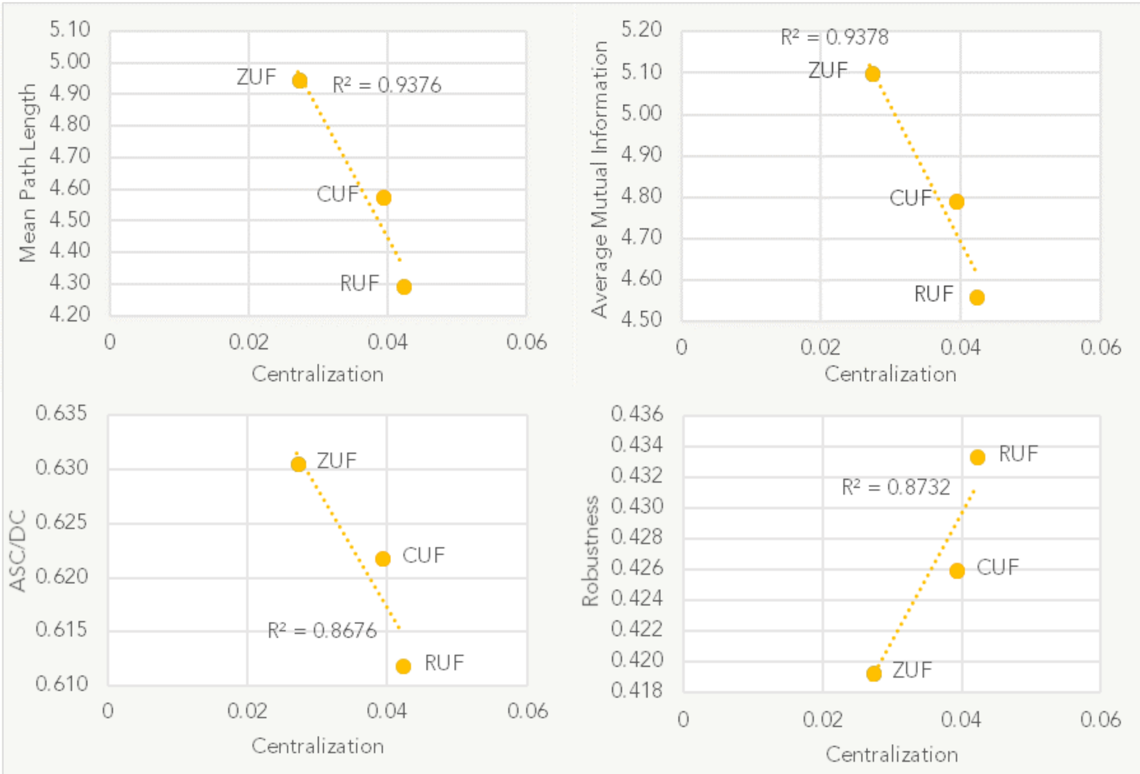


Figure 39: Non-dimensional flow metrics versus centralization for the 3 urban farm case studies without basins. Zone Urban Farm (ZUF – case 2) is the least centralized case, followed by County Urban Farm (CUF – case 3), and finally Region Urban Farm (RUF – case 4) is the most centralized urban agri-network.

As the farm actors consolidate into increasingly centralized agri-networks, the number of actors that mediate flows reduces, leading to the decreasing *MPL*. Similarly, *AMI* is reduced as the total flows become less constrained into individual flow paths. In turn, this leads to the decreasing relative *ASC* value with respect to total possible Development Capacity (*DC)* of the system, and consequently the increased *R*.

Selected dimensional metrics, including the Total System Overhead (*TSO*) and Total System Throughflow (*TST*), are plotted (in kilograms per year) with respect to network centralization for the new networks without basins in Figure 40.

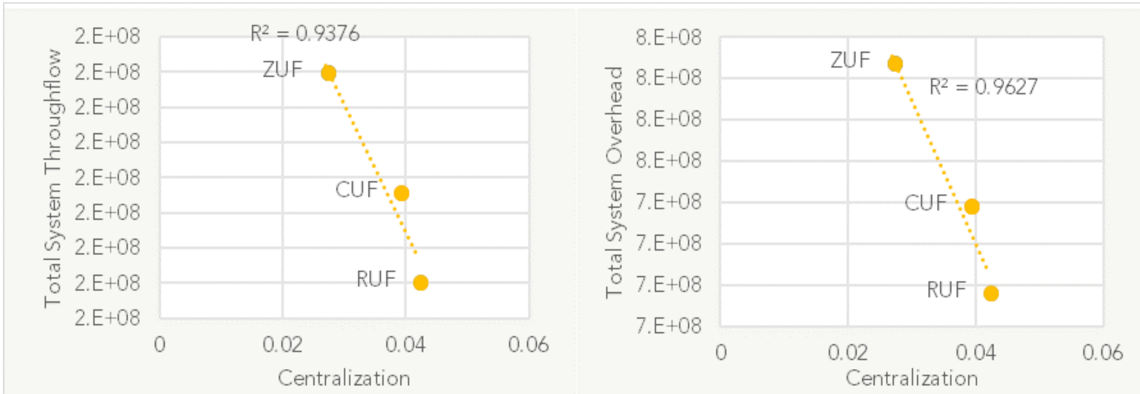


Figure 40: Selected dimensional flow metrics (in kg per year) versus centralization for the 3 urban farm case studies without basins. Zone Urban Farm (ZUF – case 2) is the least centralized case, followed by County Urban Farm (CUF – case 3), and finally Region Urban Farm (RUF – case 4) is the most centralized urban agri-network.

As networks become more centralized, fewer actors mediate flows within the network, and there are fewer transfers within the network. This results in the steep reduction in *TST*. Meanwhile, the *TSO* also decreases with *AMI* (see above). All of these observations reaffirm the discussion presented above in Section 4.4.1.

What becomes clear from these comparisons, aside from the fact that the order of the centralization scores now correctly correlates to the agri-network centralization levels, is that once the basin actors are removed from the urban farm case studies, most of the metrics now follow a much closer trend. The original plots presented in Section 4.3, where the metrics for case studies with basins are shown versus their centralization scores, the trendline had an average R^2 value of 0.53, with only 2 of the ENA metrics posessing R^2 values over 0.9 (fraction specialized predator, with an R^2 of 0.99, and connectance, with an R^2 of 0.91). The new networks, with their basins removed, show trends that follow an average R^2 of 0.83, with 1 metric trends with higher R^2 over 0.9, and only 3 metric trends with an R^2 under 0.8 (fraction specialized predator, with R^2 of 0.08, connectance (0.21), and linkage density (0.59)).

Flow magnitudes are compared across the 4 networks in the Agri-Network Experiment, both with basins (Figure 41) and without basins (Figure 42).

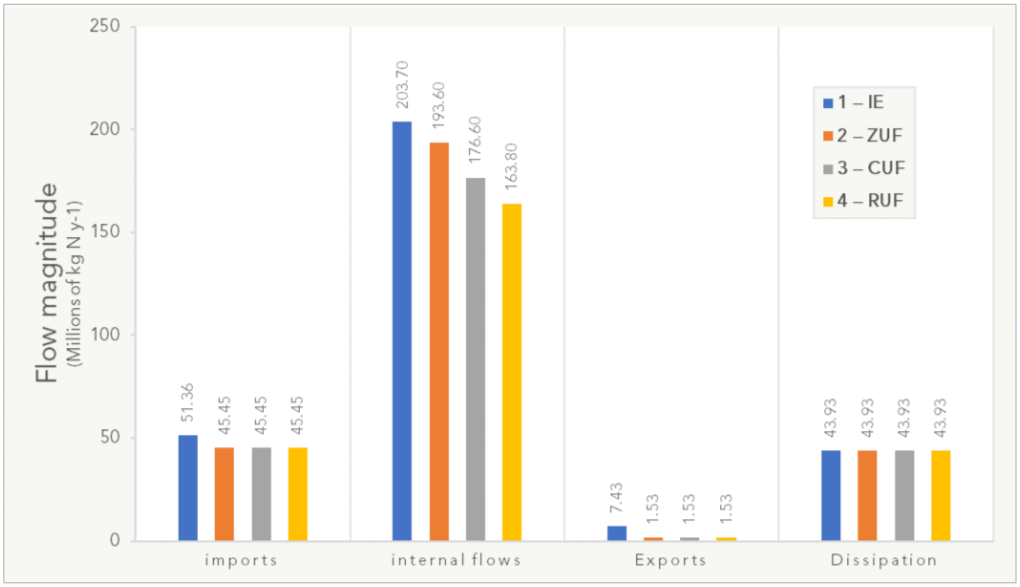


Figure 41: Selected flow magnitudes for 4 case studies with basin actors. IE – Import/Export, ZUF – Zone Urban Farm, CUF – County Urban Farm, and RUF – Region Urban Farm networks.

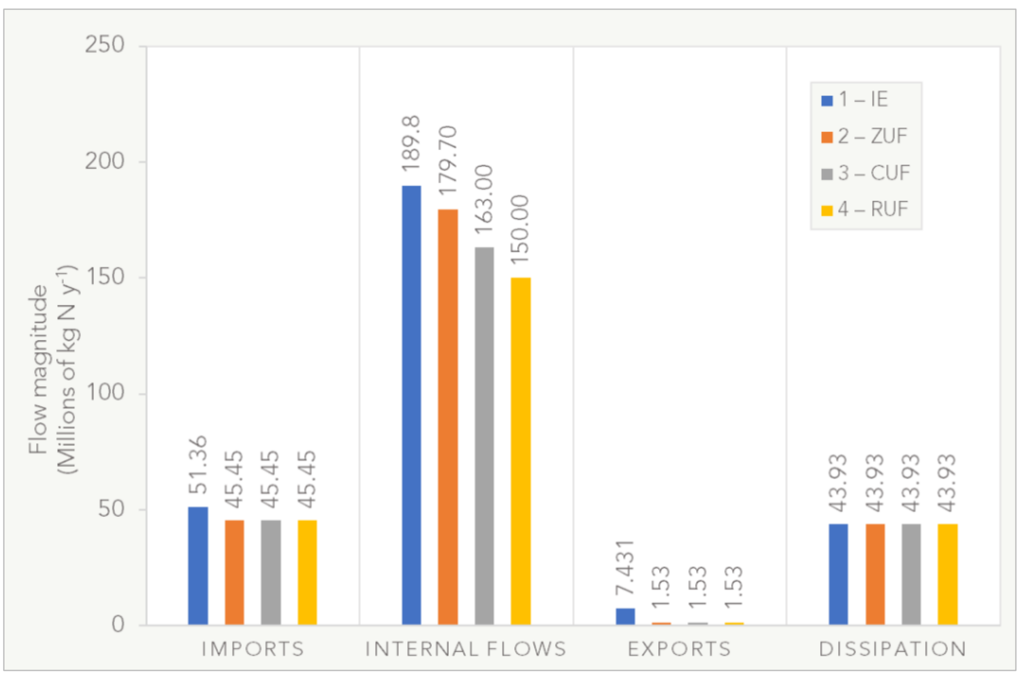


Figure 42: Selected Flow magnitudes compared across 4 case studies without basin actors. IE – Import/Export, ZUF – Zone Urban Farm, CUF – County Urban Farm, and RUF – Region Urban Farm networks.

Note the reduction in imports and exports between the baseline and the three urban farm cases (Zone Urban Farm, County Urban Farm, and Region Urban Farm). While the total amount of food eaten and grown in the region remains constant between the 4 case studies, because some of the food imports are replaced by food grown regionally, farm exports are reduced from the baseline, there is a reduction in the total amount of material flowing in the 3 urban farm cases. There is also a reduction in internal flow magnitudes from the baseline to the 3 urban farm cases on account of the consumption of regional farm goods, which results in a reduction in the total amount of material flowing into, within, and out of the system. There is a 5% decrease in the Zone Urban Farm (ZUF) case, a 14% reduction in the County Urban Farm (CUF) case, and a 21% decrease in the Region Urban Farm (RUF) case.

This difference in internal flow magnitudes between the 3 urban farm cases results from the reduction in the path lengths of imported fertilizer and feed flows, as they get converted into produce and poultry products and eventually are eaten and converted into waste flows out of the boundary. As more material-mediating actors are removed from the systems, fewer actors convey materials down to the individual zones. In the decentralized cases, the magnitudes of internal flows increases accordingly, as more and more intermediary actors handle flows. This can be seen in the steady increase in the internal flow magnitudes from the Region Urban Farm (yellow) to the Zone Urban Farm (orange) and even more so in the Import/Export case (blue). Figure 43 shows this emerging relationship between the level of centralization and the internal flow magnitude using the 3 urban farm cases (without basins).

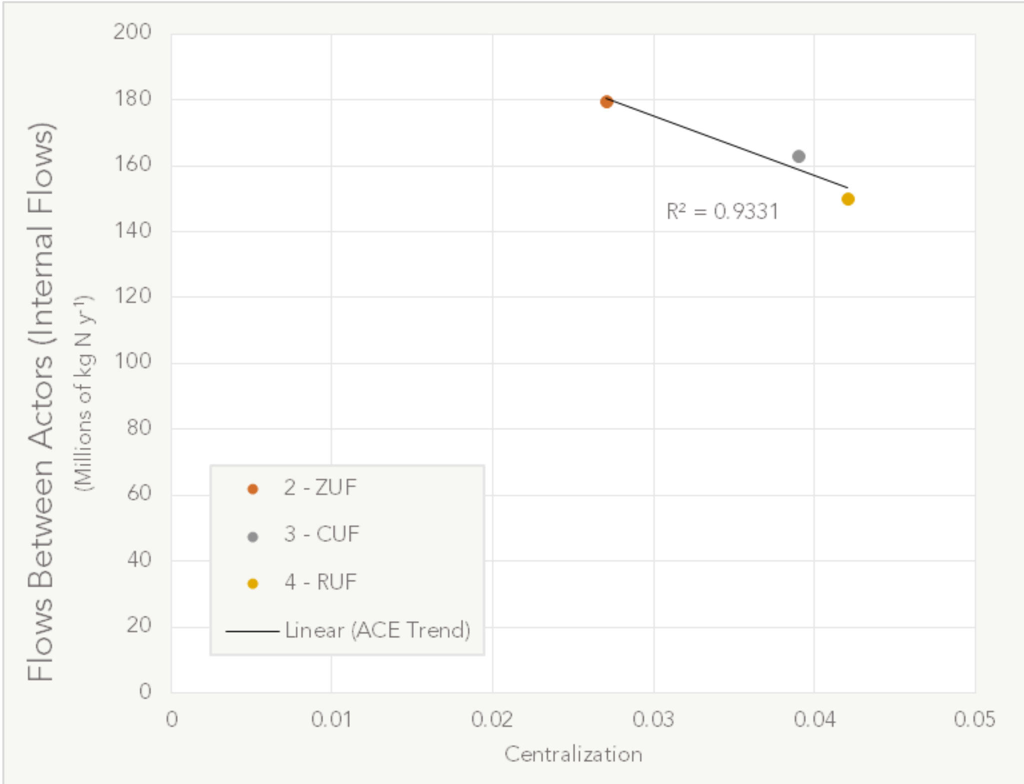


Figure 43: Total magnitude of flows between actors (internal flows) as compared to level of urban farm centralization for all 3 Urban Farm Cases, Zone Urban Farm (ZUF – case 2), County Urban Farm (CUF – case 3), Region Urban Farm (RUF – case 4). Flows reported in millions of kilograms of nitrogen per year.

As the farms become more and more centralized, the number of actors through which materials must flow in order to get to a given zone is reduced, and thus the system become less constricted. Although this may seem counter intuitive, as one may imagine a decrease in the total actors would lead to more constricted flows, the decentralized networks are actually constructed in such a way as to favor increasingly localized distribution, whereas the centralized urban farm network can distribute farm products into any zone. In other words, the less centralized networks, while they have more flow paths and longer path lengths (more intermediate actors mediating flows between import and final destination), actually constrict the geographic area to which farm products can flow. Once a farm product reaches a particular zone, it nearly always stays within the zone, as most zones do not produce an excess of food to enable collection by county farm product distributors. By contrast, farm products grown in the region urban farm is able to be consumed in any number of zones.

This difference in the level of organization and the resulting geographic constraints to flow paths can be seen when possible pathways for produce are visualized in the RUF network as compared to possible produce flow paths in the CUF network (Figure 44).

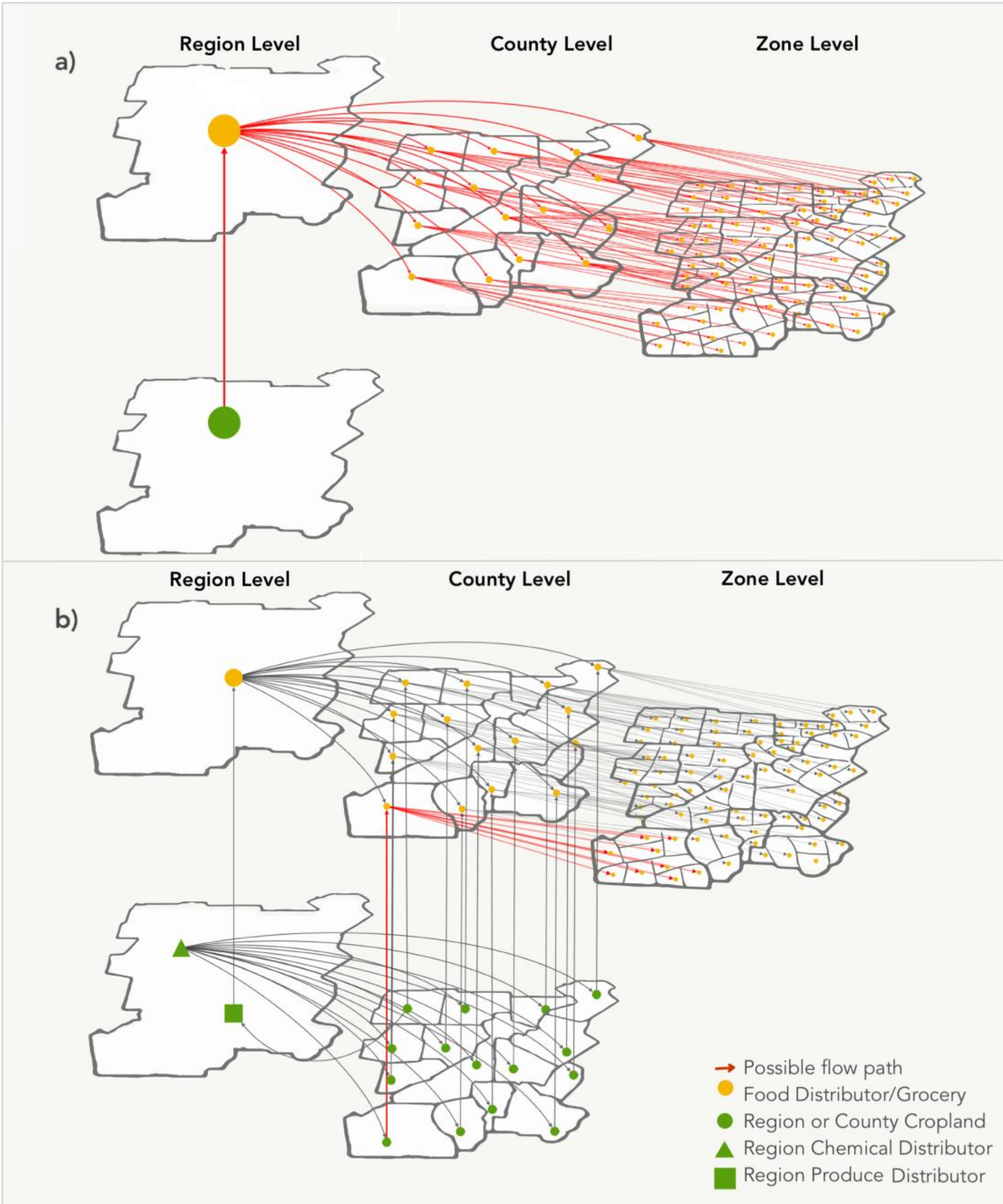


Figure 44: Potential produce product flow paths in the Region Urban Farm (RUF) case (a) and the County Urban Farm (CUF) case (b). Produce products can be delivered to any county or zone in RUF, whereas nearly all produce grown in a given county in CUF is confined to that county.

When the pathways of possible produce flow to the zone groceries are highlighted in this way, a few things become clear. First, a finished produce product grown at a county-level produce farm in CUF is almost always constricted to flow down to its respective county. This is because the network was constructed in such a way so as to favor food distribution within the geographic area. Only surplus flows (which only are present in Bartow county, in the top left corner of the county level diagram in Figure 44) are sent up to the regional produce product distributor for possible distribution within the neighboring counties via the regional food distributor. Although imported chemical fertilizer can flow to any one of the counties, ones a portion of this nitrogen import is allocated to the county, it mostly remains within the county. Conversely, an import of fertilizer to the regional urban produce farm is taken up by crops right on site, not divided and constrained to a specific county. These crops are sent then to the regional food distributor and subsequently all over the region, not confined to a smaller geographic area.

Although ecologists have many metrics by which they may gage the "health" of an ecosystem, when an abstract model is used to characterize multiple biological processes working together, as is the case with ecological systems, the results seem be contradictory or context-dependent (Ulanowicz 2009). For example, Robustness (R), which measures of the relationship between the constraints on flows within a system and the level of redundancy in the system. As mentioned in Section 3.1.2, a high R indicates lower constraints on the flows in a system, which in turn enables the system to reorganize in order to maintain function when faced with perturbations (Ulanowicz 2009). This ability to rearrange and repair in the presence of disturbance may be used as an argument for the long-term stability of systems displaying robustness.

By contrast, the increased Average Mutual Information (*AMI*), and by extension increased Ascendancy (*ASC*), metric values observed in the more decentralized urban farm scenarios indicates an increase in species specialization and efficiency mediating flows within the networks, which is a characteristic often found in more mature ecosystems that have evolved over many generations without disturbances or cataclysmic events, as species within these networks become more specialized (Bondavalli, Bodini et al. 2006). These mature ecosystems may be more brittle when faced with disturbances than those with more flow path diversity (Ulanowicz 2009). Therefore, the case studies presented in this thesis may indicate that a more centralized urban farm network, while less efficient than the decentralized case studies, would be more optimal in the face of food insecurity and threats to the food system. Indeed, the fourth and most centralized urban agri-network, Region Urban Farm (RUF) lies closer to the "window of vitality" when all networks' *R* values are plotted against their *ASC/DC* values (Figure 45).

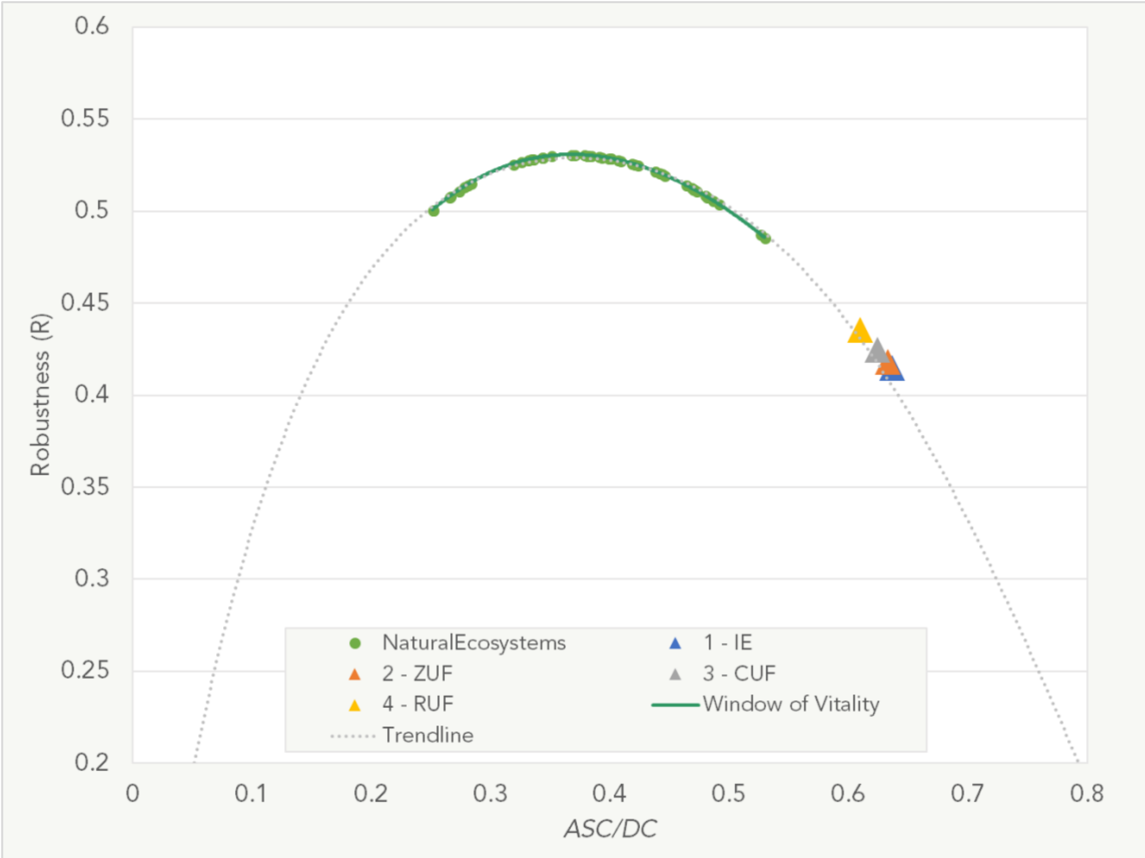


Figure 45: Robustness (*R*) plotted against Ascendency (*ASC*) over Development Capacity (DC) for Import/Export (IE – case 1), Zone Urban Farm (ZUF – case 2), County Urban Farm (CUF – case 3), and Region Urban Farm (RUF – case 4) (Ulanowicz 2009, Layton, Bras et al. 2015).

From Figure 45 one can see that the most centralized urban farm case, RUF, occupies the position closest to the window of vitality, indicating that it may exhibit a more advantageous balance between efficiency and redundancy.

The discovery that more centralized urban farm networks improve network robustness has implications for design of sustainable urban agriculture systems. It suggests that urban agriculture should perhaps be deployed within the urban boundary but in more centralized locations in order to balance robust flow paths afforded by a centralized location and the efficiency and added urban self-sufficiency of bringing the site of food production closer to the point of consumption.

4.4.2.2 Actor Aggregation

Although the observation that the Region Urban Farm Case out performs the Zone Urban Farm Case in terms of its position on the window of vitality curve seems to contradict theories that food system decentralization is more sustainable, it is important to further examine results in the ecological context. In the present study, industry actors have been largely disaggregated into hierarchical distribution actors, as is the case with all three of the variable actors (poultry, produce, and food distribution actors). This was a decision made to provide a uniform organizing structure that could be modified into varying levels of centralization in order to test the zone food network hypotheses. However, this is a deviation from common practice in both ecology and industrial or urban applications of ENA. Ecologists often aggregate species actors into trophic actors in an effort to encapsulate global trends (Wilson 1999). Layton (2014) found that aggregation has varying degrees of impact on ENA metrics: some of the metrics, such as species richness, connectance, and linkage density, depend strongly on mathematical quantities associated with the number of links in the network. In such cases, aggregation does impact these metrics. For the other metrics, however, Layton could not conclude with certainty whether species aggregation would affect the outcome of analysis.

Aggregation has also historically been the practice in urban applications of ENA. Nearly all urban ENA studies combine actors into broad categories; however, these broad aggregates may not always follow the trophic functional groups, or they may lose resolution that could provide insight into their overall network behaviors. For example, Zhang, Yang et al. (2010) produce a network model to analyze four Chinese cities in which they designate five distinct compartments and quantify the flows between these. However, this area is not yet completely understood by ecologists, and it is unclear whether aggregated groups in existing urban ENA studies are designated in a manner that reflects natural systems, or whether they adequately convey information about the networks' functional roles.

While it can be convenient, the act of aggregating species into broader compartments has presented problems for ecologists. Levin (1992) notes that biases can arise from an ecologist's choice of scale and aggregation. He notes that there remains a critical question in ecology as to whether there is a natural hierarchical breakdown of ecological networks into aggregates, or whether a given aggregation scheme imposes an unnatural or arbitrary filter on an otherwise continuous spectrum of functional roles. Aggregation can lead to strong decreases in network ascendency by increasing the possible routs along which material and energy can flow between compartments (Ulanowicz 1986). Ulanowicz and Kemp (1979) propose a procedure to approximate compartmentalized flow networks that minimizes this impact on ascendency by carefully and aggregating species based on their trophic position and network function. While their procedure simplifies the process, it also requires the removal of weaker connections and introduces challenges regarding how to deal with non-living compartments such as detritus pools. Moreover, trophic aggregation does not capture the sequential flow of material or energy within the studied ecosystem, and can still lead to significantly reduced ascendency values (Christensen and Pauly 1992, Allesina, Bondavalli et al. 2005). Finally, because the act of aggregating species into compartments requires the removal of some links between weakly-connected actors in the network, this has been demonstrated to strongly impact the appearance of network cycling behavior, in some cases leading to exponential increases in the number of cycles found (Allesina, Bodini et al. 2005).

In the present study, one may make the case that the more “centralized” urban farms in the urban farm case studies presented in the Agri-Network Centralization Experiment (ACE) (see Section 4.3.2) are merely representative of more aggregated versions of the less centralized Zone Urban Farms present in the second case study (Zone Urban Farm Case). Following in this logic, the ENA results indicating that the more centralized networks are more robust than the disaggregated localized network are to be expected. To test this hypothesis, a modification to the Region Urban Farm Case (RUF-case 4) is made by absorbing the “crop” actor into the “farmland” actor (Figure 46).

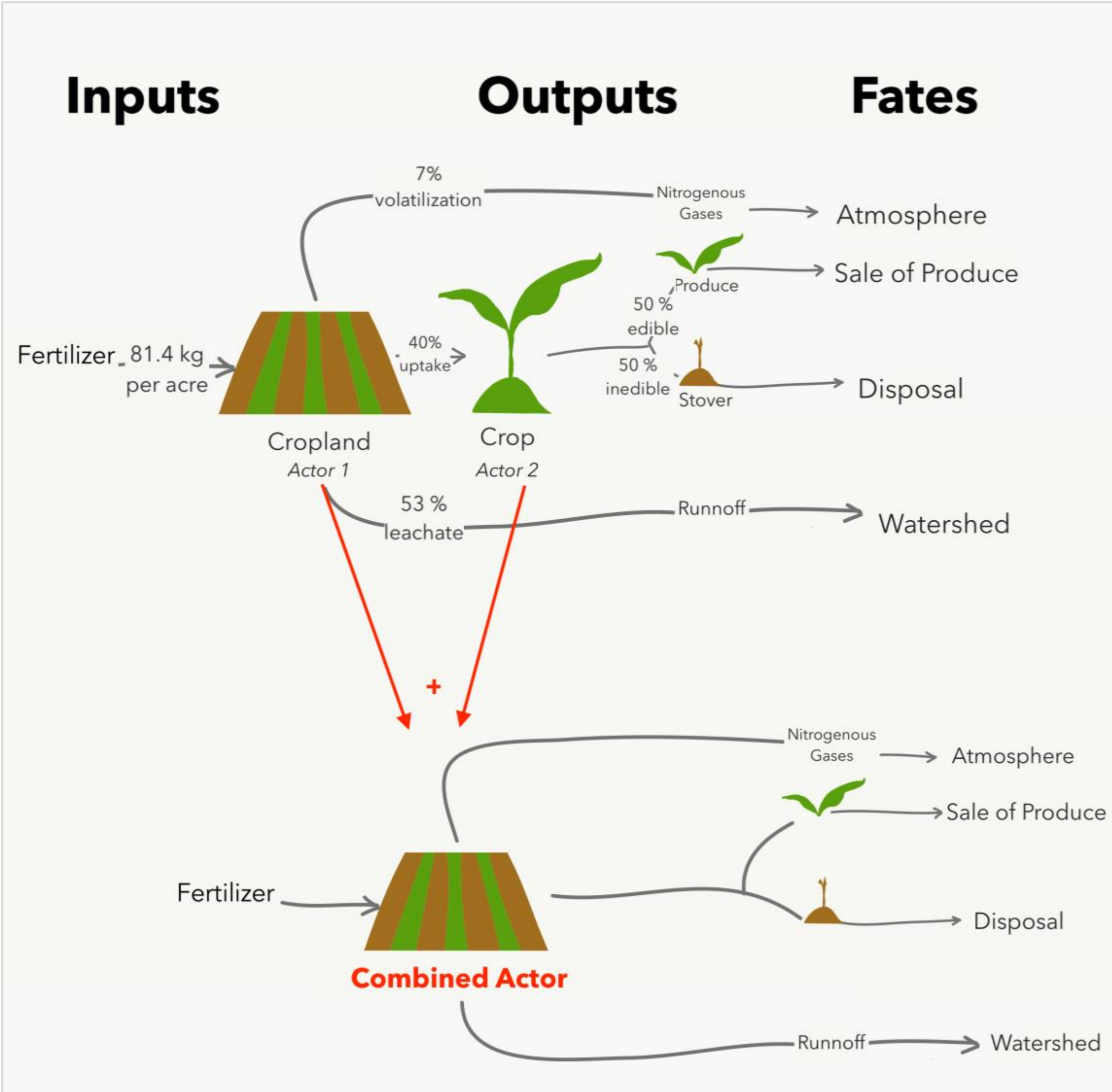


Figure 46: Crop and Cropland actor aggregation.

In the original case study, the region-level cropland actor has 3 pathways along which its nitrogen outputs can flow (to dissipation, Chattahoochee, or crop) and the crop actor has 2 pathways (to regional food distributor or to dissipation). In the modified network, the cropland actor now has a new link to the regional food distributor, and the proliferation of flows of nitrogen from the cropland actor are thereby less constrained.

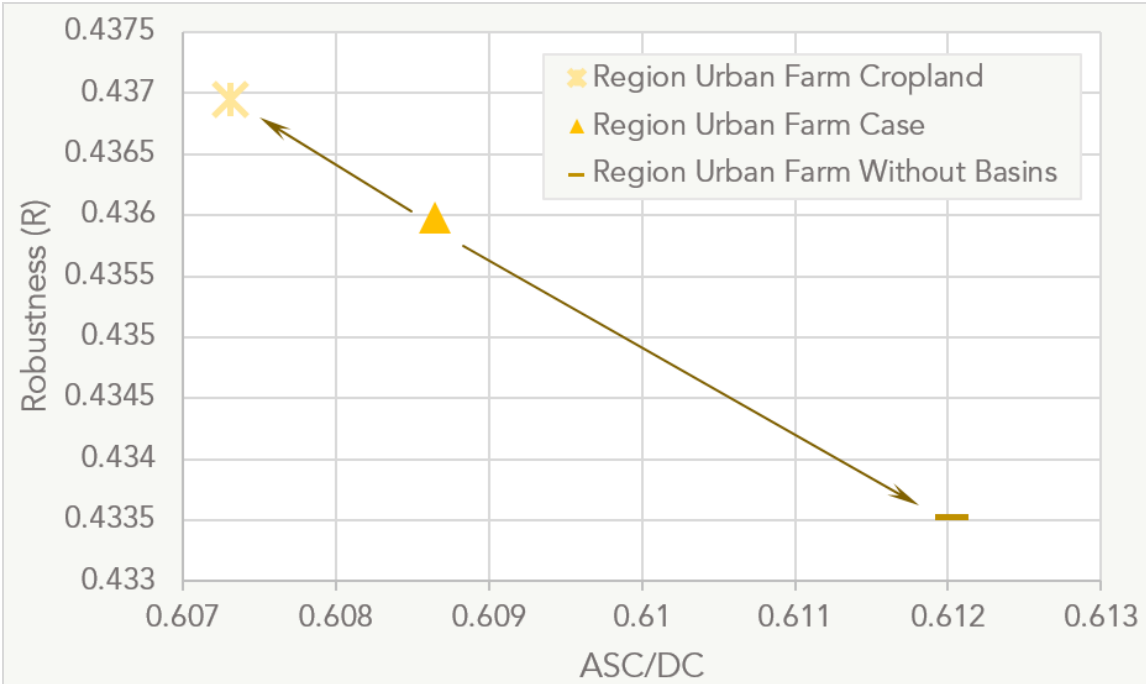


Figure 47: Efficiency vs. Robustness plotted for Region Urban Farm Case with 2 modifications: 1) "Crop" actor intermediary between Region Cropland and Region Food Distributor (*), 2) Chattahoochee water basin actor removed from the network (-).

Although the change wrought by this aggregation of crop and cropland are very small in this case, it demonstrates that actor designation and the degree of aggregation selected by the system designer or analyst can have impacts on the quantified ecological network performance of the system. Without changing the amount of material that is transferred between the produce and food distribution industries, one can manipulate the appearance of ecological "fitness" of the network. Similarly, the inclusion of the basin actors in the case studies in the Agri-Network Centralization Experiment (ACE) seems to impact the balance between Robustness and Ascendancy over Development Capacity in different ways and to different degrees. This is exhibited in Figure 48 for the second and third case studies, Zone Urban Farm (ZUF) and County Urban Farm (CUF) by removing basin actors and plotting the resulting *R* and *ASC/DC* values.

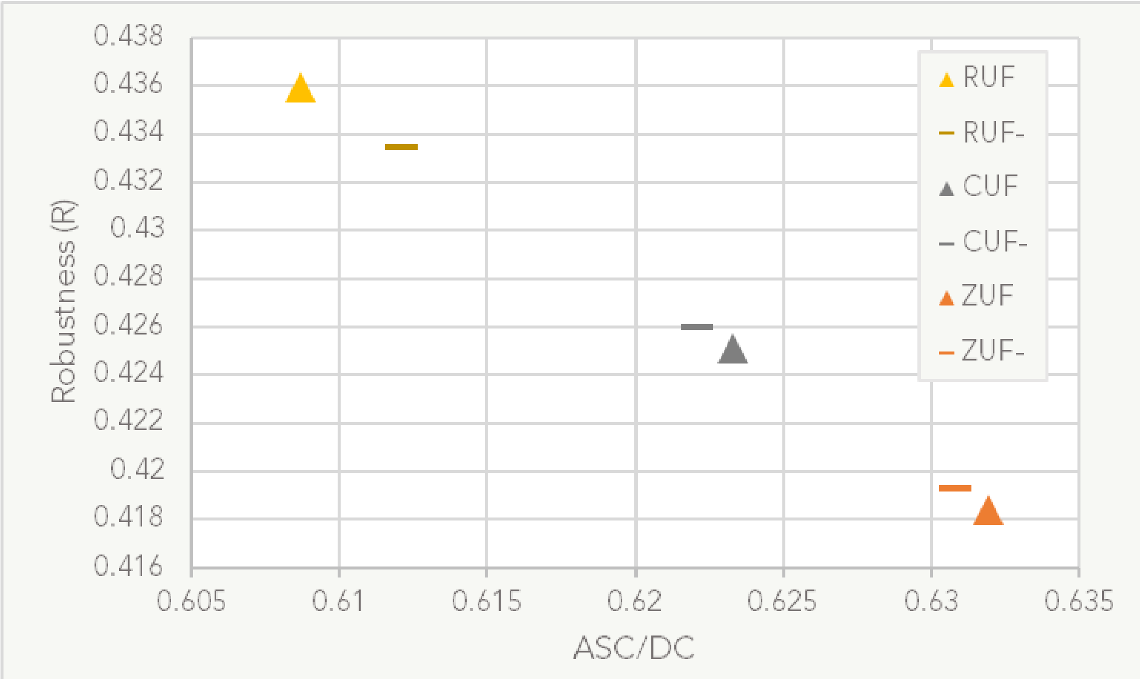


Figure 48: Balance between Robustness (R) and Ascendancy over Development Capacity with and without basins for Zone Urban Farm (ZUF and ZUF-), County Urban Farm (CUF and CUF-), and Region Urban Farm (RUF and RUF-).

In the second and third case studies, the change brought on by remove of these basin actors is even smaller, but to an opposite effect. In the third case study (CUF), the removal of the basin actors slightly improves the robustness of the system, while in the second case study (ZUF), the removal also improves its position to a slightly larger extent. This can be attributed to the fact that the CUF case study contains connections between 28 actors (2 farms in each county except for DeKalb, who has no Poultry Farm) to only 5 basins. Thus, removal of the basin actors seems to increase the redundancy and lead to a slightly improved Robustness value.

Although the changes illustrated above to Robustness and Ascendancy to Development Capacity brought on by removal of the basins may seem trivial, as they are artefacts of the actor designation, the resulting changes demonstrate the need for uniformity in aggregation decisions. In order to appropriately compare networks using ENA, it is important to adapt the strategies proposed for trophic aggregation for use in Industrial and Urban Ecology studies (Ulanowicz and Kemp 1979). Moreover, the discrepancies wrought by the actor designations explored above illustrate the need for further these strategies should be explored in much greater depth as they apply to human systems in order to properly apply ENA for use as a design tool.

4.4.3 Model Constraints, Unknowns, and Limitations

4.4.3.1 Import Uncertainty

This study uses several simplifying assumptions in order to construct the models for the baseline and "Urban Farm Scenario" case studies. As previously mentioned, the baseline case study assumes that all food is imported into the system. This is partially based on the network analysis of food flows in the US, which looked at total foodstuffs imported to the Atlanta-Sandy Springs-Gainesville statistical area in 2007. This contained a population of about 5.9 million people in 2007. Based on the estimate proposed in this study for total nitrogen (N) imports of 19.18 g per capita per day, or 113,353.8 kg of N per day for the network, for a total of 45,606.75 tons of N purchased per year. When an average N content of food of 0.0228 kg N per kg food is used, this would lead to an estimation of 2 million tons of food, which is only 23.3% of the CFS food import estimated. found that a total of 8.6 million tons

The discrepancy between the calculated imports could be attributed to a variety of factors, most notably food packaging, which is included in the weight recorded by the CFS; however, it is unlikely that 75% of the product's weight is packaging. Additionally, the 0.0228 kg N per kg food estimate is based on an equal distribution of food products (Cease, Capps et al. 2015), for which there is a range from 0.0109 kg N/kg food for fats and oils, to 0.0364 kg N/kg food. However, if the lower end estimate is used, the estimate increases to 4.2 million tons of food, which is still under 50% of the CFS estimate. This might mean that either Atlanta residents are either wasting far more food than predicted or purchasing more than predicted by the baseline estimates used in this study.

A third alternative source of discrepancy is the data used by Lin, Dang et al. (2014) in their CFS analysis may have included foodstuffs that are not directly consumed by the population, or they vary from the scope of this study. For example, the CFS used in their study groups commodities such as animal feed and other products of animal origin, and include alcohol, tobacco, agricultural products (including feed and forage products) and beverages, which are not considered directly in this study.

If poultry feed imports to the baseline network configuration are considered, an additional 11.4 million kg of N, or 447,888.69 tons of feed, bringing the feed plus food import weight to 2.5 million tons, or 4.5 million tons if the lower end of N concentration is considered. However, this, again, is not a one-to-one comparison, as the statistical area covered includes much higher volumes of poultry production, in addition to cattle, swine, and additional varieties of livestock not in the scope of this study. Higher-resolution data that considers the actual mass of N imports to the system area are lacking in the literature, and thus the estimates proposed in this study provide a reasonable template for future iteration.

4.4.3.2 Diet Pattern and Waste Uncertainty

Rose, Parker et al. (2015), in their review of feces and urine characterization studies, find that the largest factor affecting N excretion is dietary intake of protein. The N contents of urine increase with higher levels of protein in the diet. One FAO/WHO study found the safe rate of nitrogen intake to maintain nitrogen balance is 0.75 g protein/kg body weight/day (Baum and Greenwood 1958). As a guideline figure of nitrogen voided in feces scientists concluded that when a healthy human is in nitrogen equilibrium, nitrogen excretion will equal ±5% of intake (Rose, Parker et al. 2015).

Variation in the protein content of feces is largely dependent on protein intake in the diet; however, the digestion rate of protein has been shown to vary from 69% to 93% as a result of differing types of protein in the diet, including variation due to vegetative or animal source (Rose, Parker et al. 2015). It should be noted that most of nitrogen output is in the urine fraction with this study showing that only 14% is voided through the feces (1.8 g/cap/day) and the majority is excreted in urine (10.7 g/cap/day). Ranges for urine and feces N were recorded as 2-35% and 0.9-4.9% respectively, revealing a broad range of values for total N waste content. As this is the main attribute used to quantify food intake, food waste, and wastewater flows, it stands to reason that this is the largest source of uncertainty in the model.

4.4.3.3 Connectivity and Network Construction

A survey of available data revealed that while the popularity of composting food waste is growing (Gunders 2012), data detailing food waste composting rates and zone food consumption in the Atlanta Metropolitan Region are extremely limited. Additionally, there is presently no infrastructure or regulatory framework to divert food waste from landfill (Beck 2005, Georgia Department of Natural Resources 2018). Estimates characterizing the region's food waste diversion rates in 2016 were under 1% of the food waste creation totals calculated in this study (Girard, Griffin et al. 2017). In other words, the limited data estimating the amount of food waste that is composted indicates that it represents only a small fraction of food wasted in the region, and there is no additional information regarding end uses for said compost. Thus, the baseline network is constructed neglecting food waste nitrogen recycling and zone consumption. However, it is likely that the cycling and overall network connectivity is much more complex in the region than any of the networks constructed here.

Additionally, this study only evaluates cropland onto which chemical fertilizer is supplied and its resulting products, neglecting pastureland and food products grown for livestock. As a result of these assumptions, the models explored here exhibit no cycling and likely underreport the amount of agriculture products grown within the region boundary and underestimate the amount of zone food sourcing in the baseline scenario. More data will be needed in order to adequately quantify the cycling afforded by compost application, manure use, and connections between produce and poultry industries in future models.

An additional shortcoming of the presented case studies is their simplified connectivity. The results demonstrate very low Linkage Density, Connectivity, Prey-To-Predator Ratio, Generalization and Vulnerability values, as well as very high Ascendancy and Average Mutual Information metric values. These are likely due to the simplified one-to-one connections between actors that is used to characterize the systems. Figure 49 presents an additional network representation using a hierarchy network diagram to highlight the limited connectivity between predators and prey. Notice that most prey correspond to only one or a few predators, and similarly, most predators receive inputs from only one or a few prey.

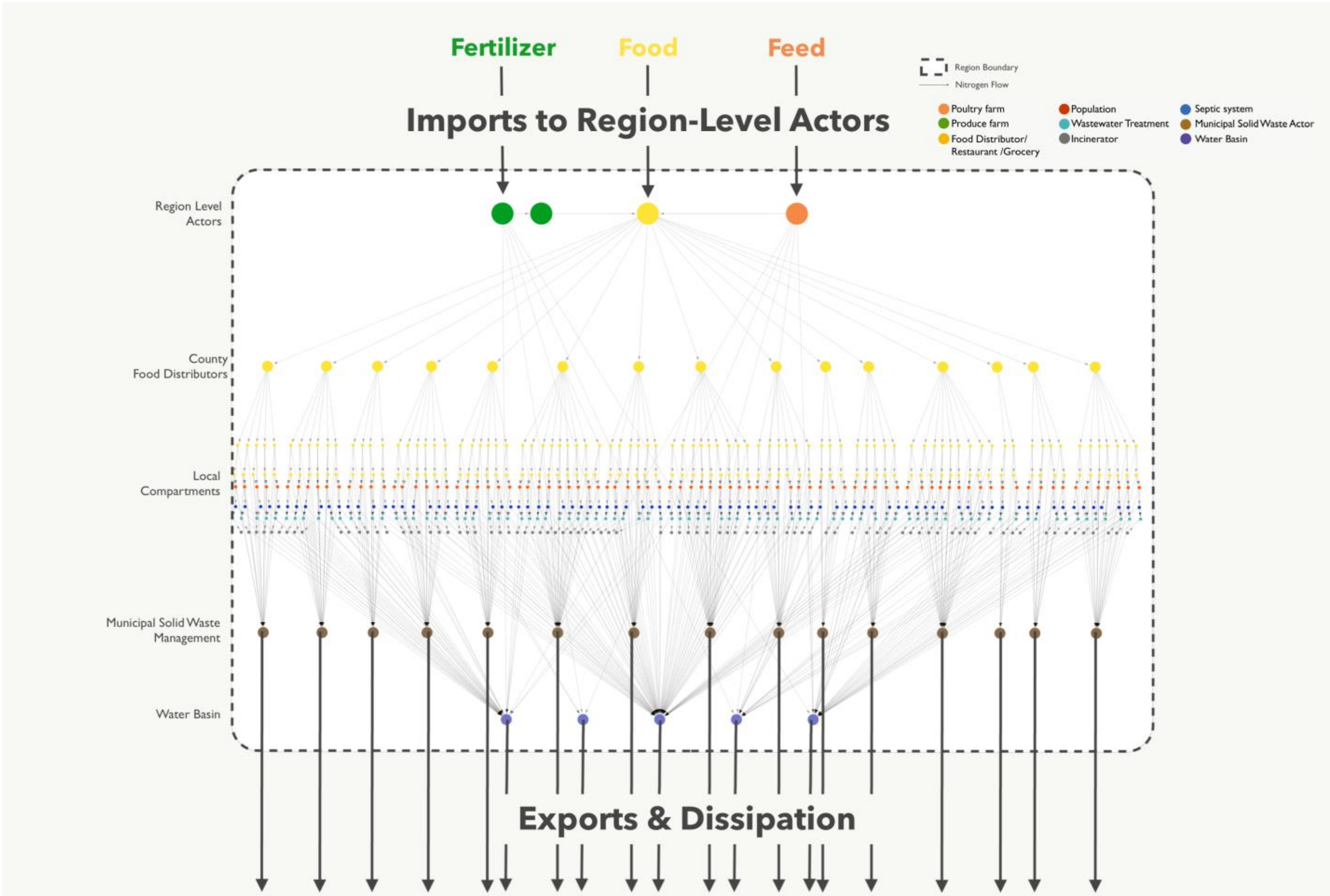


Figure 49: Network visualization of Region Urban Farm (RUF – case 4) network. The presence of many parallel lines and one-to-one predator-prey actor linkages demonstrates the high degree of specialization characterizing the network's construction.

In a more complex network construction that more accurately represents the food network in the Atlanta Metropolitan Region, the values for the ecological network metrics would likely demonstrate higher levels of cycling, higher prey to predator and predator to prey ratios, and more favourable balances between redundancy and efficiency than the simplified characterizations presented here.

4.5 Summary of Agri-Network Centralization Experiment

The first experiment explored in this thesis was designed to test the hypothesis that zone food production systems are more environmentally sustainable using ecological network analysis and network centralization indices. The experiment answered the following questions:

- How does network performance, as measured by ecological network analysis, differ between systems that import all food and systems where food is sourced from within the system boundary?

- When food is sourced within the system boundary, what level of agri-network centralization produces the most favorable ecological network performance?

- Can a correlation between conventional ENA indices and the degree of food system centralization be established?

Results suggest that increased urban self-sufficiency and reduced environmental burden can be achieved when food is produced within the urban boundary. This is demonstrated by the improvement in ecological network metrics from the baseline to the 3 urban farm case studies and by the reduction of impacts due to food miles. However, decentralization of this production into localized food sub-networks confines flow paths and reduces overall robustness. The most centralized urban agri-network comes closest to achieving a healthy balance between redundancy and efficiency, while a decentralized system displays more efficient transfer of materials, thus resembling a more mature ecosystem with more specialization. The results also suggest that a decentralized urban farm network, as constructed, may be more fragile to disruption, with highly specific food sourcing and confined flow paths that do not allow for restructuring in the event of a perturbation. A more realistic model should be constructed in which zone populations have a diverse set of groceries and restaurants from which they can purchase foods, and where zone farms have the ability to distribute to a variety of groceries and potentially directly to restaurants and populations. This will likely result in more favorable network metrics such as redundancy and flow path flexibility that could shift and adjust when faced with disturbed food supply.

CHAPTER 5. FOLLOW-UP EXPERIMENT: NUTRIENT OPTIMIZING MODULES

Through the Agri-Network Centralization Experiment, it was found that urban agriculture systems can outperform a system in which no food is obtained from agriculture within the system boundary from an ecological network performance perspective. However, it was also determined that increasingly decentralized urban agriculture networks, where food is grown and consumed locally, are not as robust as a centralized urban agriculture system. While at first this seems to contradict the assertion that local agriculture is better, many proponents of urban agriculture site increased opportunities for cycling as a critical justification for local food systems (Feenstra 2009, Girard, Griffin et al. 2017, Goldstein, Hauschild et al. 2017). As mentioned previously, the scenarios presented in the Agri-Network Centralization Experiment (ACE) do not include detrital actors or recycling. Recognizing this deficit, the Nutrient Optimizing Module (NoM) experiment is a follow-up to the first experiment that attempts to provide the missing piece of the urban farm scenario in the ACE. This follow-up experiment is designed to test the effects of increased cycling in the most decentralized case study on systems performance from an ecological network perspective.

The following sections present an overview of the NoM experiment (Section 5.1), followed by Section 5.2 a description of the methods used to construct this fifth case study using the additional nutrient cycling actors. Section 5.2.1 provides a more detailed outline of the actors in the NoM and the nitrogen flow assumptions made in this experiment. Section 5.2.2 describes the network construction used for the NoM case study. Next, the

NoM case study is evaluated for its network performance using metrics outlined in Chapter 3, and the results are presented and discussed in Section 5.3, within the broader urban agriculture context first explored in Section 4.4. Finally, all 5 of the different case studies and their network performance and impact results are contextualized with respect to urban resilience and urban self-sufficiency in Section 5.3.3.

5.1 Nutrient Optimizing Modules (NoM) Experiment Objectives and Overview

Prior urban and industrial ecology studies have shown that in order for human ecosystems to more closely resemble natural ones, they must incorporate detrital actors that process consumers' waste streams and recycle these materials and energy (Layton, Reap et al. 2012, Layton, Bras et al. 2016). As mentioned in Section 2.3, one may initially consider wastewater and municipal waste collection actors to be detritivores. However, true detrital and decomposer actors make materials from "higher" level organisms (like animals) available for producers (i.e. plants), while the waste management actors outlined in the Agri-Network Centralization Experiment (ACE) case studies merely convey waste products out of the system (see Section 4.2.2). For this reason, the Nutrient Optimizing Module (NoM) Experiment incorporates biotechnology modules in a fifth case study, the NoM Case, which is a modification of the most decentralized urban farm scenario case study from Experiment 1 (ACE), the Zone Urban Farm Case (Case 2 – ZUF).

The actors in the NoM (case study 5) model are connected to the wastewater treatment facilities, septic systems, restaurants, and grocery stores in the zones to reduce the magnitudes of wasted nitrogen in the form of food waste, septage, human biosolids, and wastewater effluent nitrogen described in Chapter 4. The biotechnology actors introduced in NoM recycle this nitrogen in the form of soil nutrient, which is sent to zone cropland, as well as fish and additional crops, which are sent to zone grocery actors. Section 5.2 outlines the actors introduced in the NoM case study, as well as their associated nitrogen flows and connections in more detail.

5.1.1 Research Questions

The NoM experiment seeks to answer the following research question presented in Chapter 1:

- How do ecological network performance, agri-network centralization and embedded life cycle impacts change when biological actors are introduced as recycling modules?

5.1.2 NoM Experiment Tasks

The NoM case study is constructed and analysed using the network performance metrics described in Chapter 3 using the following research tasks first introduced in Section 1.2:

<u>Task 2a: Additional Actors Introduced</u>

The NoM case study uses emerging biotechnologies to reroute some of the nitrogen waste streams identified in Experiment 1 to recycling actors. These actors include black soldier flies (BSF), who can eat a variety of food and human wastes with high nitrogen efficiency (meaning they convert a large percent of feedstock nitrogen to biomass). BSF are introduced in the NoM case study to upcycle human biosolids produced in conventional wastewater treatment and septic systems in the ACE case studies (see Section 4.2.2). They also are added in place of municipal solid waste actors for food waste inputs. they produce a nitrogen-rich soil conditioner as a biproduct (Diener, Solano et al. 2011, Banks, Gibson et al. 2014, Nguyen, Tomberlin et al. 2015).

Constructed wetlands (CW) planted with duckweed are introduced to filter wastewater effluent otherwise discharged or land-applied in the ACE case studies (see Section 4.2.2). They are introduced here due to duckweed's ability to filter nitrogen from waste water and retain this nitrogen in their own biomass (Hillman and Culley 1978, Körner and Vermaat 1998). Both BSF and CW provide nutritious feed alternatives to existing livestock feeds (Culley and Epps 1973).

Aquaponic plants and fish are introduced as additional food products due to findings that the combined cultivation of fish and plants provide a more efficient use of nitrogen inputs (Hindelang, Gheewala et al. 2014, Yogev, Barnes et al. 2016, Cohen, Malone et al. 2018). Aquaponics also requires less space than conventional grow strategies, making it a promising urban agriculture production strategy (Love, Fry et al. 2014). The assumptions used to determine the conversion rates and flows for each actor will be described in more depth in Section 5.2.

Task 2b: Modifications of Network from Experiment 1

The actors introduced in Task 2a are then added to the most decentralized network from Experiment 1 (Case 2 – Zone Urban Farm Case) at the zone level. Black soldier flies replace the municipal solid waste management actor from the Zone Urban Farm Case (ZUF) as the receiver of solid food waste from zone restaurants, groceries, and population actors. They also become the recipient of human biosolids and septage from the wastewater treatment plants and septic system actors at the zone level. Wastewater treatment plant effluent is rerouted from land application and discharge to constructed wetlands, where duckweed absorb influent nitrogen. Crop stover from zone farmland is used to provide additional biofuel for anaerobic digesters that power the NoM pumps. Aquaponic fish are fed the duckweed and black soldier fly biomass, in turn fertilizing aquaponic plants. Both fish and plants are then harvested and sent to zone grocery stores, further offsetting imported foods. Aquaponic aste sludge and crop waste are sent to anaerobic digesters to power the aquaponic pumps.

Task 2c: Analysis of Case Study

Following the strategy used in Experiment 1 (ACE), the NoM network (Case Study 5) is evaluated for ecological network performance, as well as centralization and modularity. These results are presented in Section 5.3.

Task 2d: Compare All Case Studies

Finally, the last step of the NoM experiment is the side-by-side comparison of all 5 case studies presented in this thesis. Networks are compared for their relative network performance, using both ENA and Network Centralization. They are also compared with respect to imports, internal flows, exports, and waste. The relative environmental impacts of imported materials as well as emissions to the neighboring water basins are also compared between the case studies.

5.2 Materials and Methods

5.2.1 Overview of Study and System Boundary

The purpose of the Nutrient Optimizing Module (NoM), as introduced in Section 1.2, is to propose network augmentations to a simplified food network model to increase the amount of nitrogen cycling in the Atlanta Metropolitan Area. The biotechnology modules introduced increase the amount of nitrogen that is retained in the system by producing additional food products with the biproducts from waste created elsewhere in the system.

5.2.1.1 Actor and Flow Overview

As mentioned in Section 1.2.3, the actors introduced in the NoM case study are:

1. Black soldier flies (BSF)
2. Aquaponic fish
3. Aquaponic plants
4. Constructed wetlands (CW)
5. Anaerobic digesters

Figure 50 illustrates the actors included in these modules.

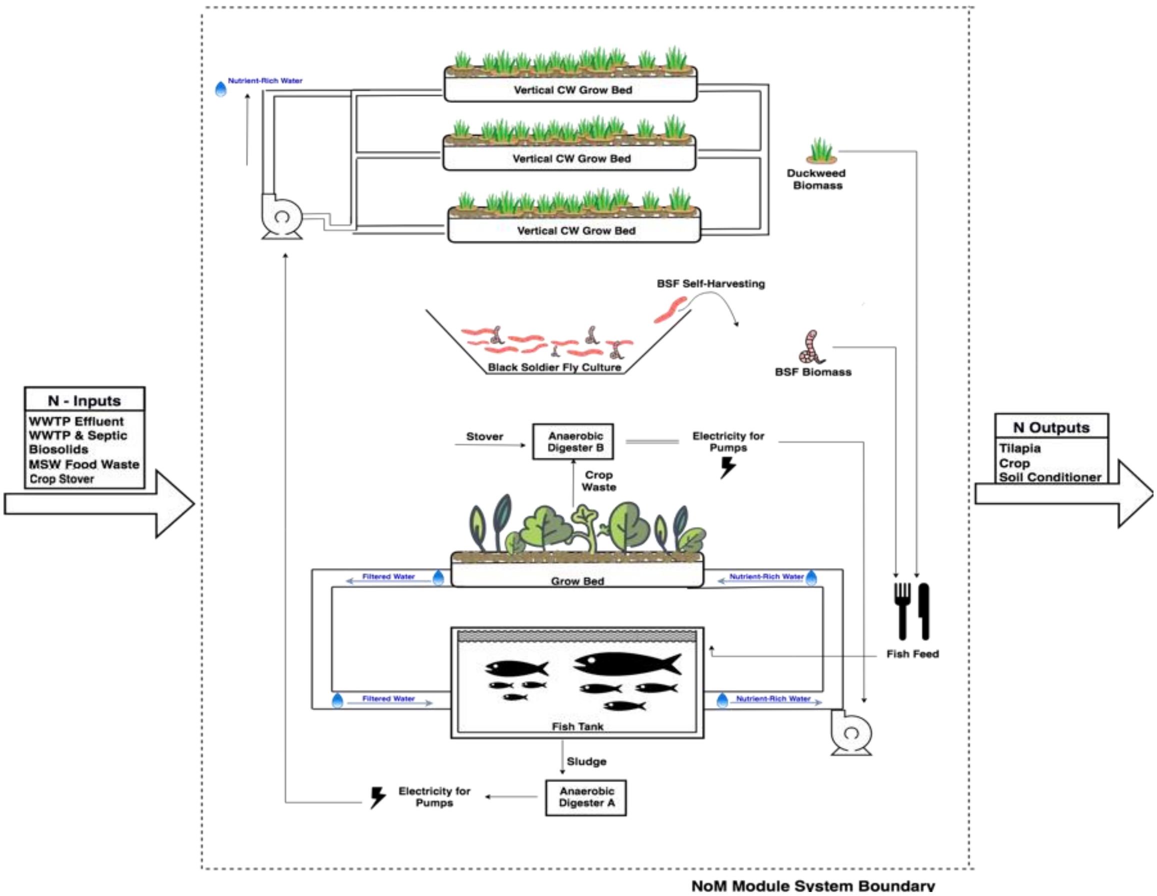


Figure 50: NoM actors and module schematic.

5.2.1.2 <u>Biotechnology Assumptions</u>

The fifth and final case study explored in this thesis tests the hypothesis that by incorporating recycling into decentralized urban farm networks, one can improve the network performance of the food network and bring its ecological network indices closer to those exhibited by natural ecosystems. The NoM case study employs the following assumptions:

1. Black soldier flies are fed human biosolids, septage, and municipal solid food waste (Diener, Solano et al. 2011, Lalander, Diener et al. 2013, Banks, Gibson et al. 2014, Nguyen, Tomberlin et al. 2015).
2. Constructed wetlands are assumed to use recirculation and adequate land area to enable full nitrogen recovery by duckweed (Körner and Vermaat 1998, Cheng, Landesman et al. 2002, El-Shafai, El-Gohary et al. 2007, Zhang, Chen et al. 2014).
3. Aquaponic fish are fed black soldier flies and duckweed (Hillman and Culley 1978, El-Shafai, El-Gohary et al. 2007).
4. Aquaponic plants are fertilized by aquaponic fish waste (Trang and Brix 2014, Goddek, Delaide et al. 2015, Yogev, Barnes et al. 2016).
5. A sufficient standing stock of aquaponic fish and crop stover are maintained to provide anaerobic digesters with enough aquaponic wastes to fully power pumps and maintain energy-neutrality (Yogev, Barnes et al. 2016).

5.2.2 Actors and Associated Nitrogen Flows

5.2.2.1 Black Soldier Flies: Assumptions and Constants

For the black soldier fly (BSF) component of the nutrient module, human biosolids and municipal solid waste N is diverted from their end fates in the BAU model and recycled as BSF feed. The total amount of BSF biomass is determined entirely by the presence of feedstock (solid food waste, wastewater biosolids, and septage). Table 17 outlines the assumptions made about growth rate and nitrogen composition by mass. Additionally, losses from volatilization of N due to background processes were taken from experimental literature conducted on food waste compost (Sullivan, Bary et al. 2002).

Table 17: Black soldier fly system parameters and variables. Parameters listed with assumed values from the literature.

Abbreviation	Unit	Meaning	Value
N_{feed}	kg N day^{-1}	N flux through feedstock	calculated
FCR_{BSF}	kg feed (kg BSFL)$^{-1}$	Feed conversion ratio for black soldier fly larvae[1,2,3,6]	5
NE	% of feed N	N efficiency[6]	50.4 ± 5
$N_{BSF\text{-}bio}$	kg N day^{-1}	N assimilated in BSF biomass	calculated
ff_{vol}	% of feed N	Feed fraction volatilized[7]	10
ff_{res}	% of feed N	Feed fraction egested (residue) [6]	39.6
N_{res}	kg N day^{-1}	N evacuated as BSF residue	calculated
N_{vol}	kg N day^{-1}	N volatized before consumption	calculated

[1] (Nguyen, Tomberlin et al. 2015)
[2] (Lalander, Diener et al. 2013)
[3] (Banks, Gibson et al. 2014)
[4] (Smetana, Palanisamy et al. 2016)
[5] (Diener, Solano et al. 2011)
[6] (Oonincx, van Broekhoven et al. 2015)
[7](Sullivan, Bary et al. 2002)

The total biomass, residue, BSF production and nitrogen volatilization is calculated (equations 32-35) based on the above values, using feedstock nitrogen derived as follows:

$$N_{feed-BSF} = Total\ MSW\ N + Septage\ N + WWTP\ N\ solids \quad (32)$$

where *MSW N* is nitrogen from municipal solid waste from restaurants, grocery, and population actors within the zone, *WWTP N* is nitrogen contained in biosolids produced in wastewater treatment facilities in the zone.

The total nitrogen retained in BSF biomass is calculated using the nitrogen efficiency NE_{BSF} and nitrogen contents of the feedstock N_{feed} as follows:

$$N_{BSF-bio} = N_{feed} \times NE_{BSF} \quad (33)$$

where $N_{BSF\text{-}bio}$ is the nitrogen contained in BSF biomass.

Given the volatility of ammonia and decomposing organic matter, a portion of this residue volatilizes. It is assumed that a portion of feedstock will begin to decompose, releasing nitrogen in the form of ammonia before it is completely eaten by the black soldier flies. The magnitude of nitrogen that is lost to the atmosphere (N_{vol}) before it can be consumed is calculated as follows:

$$N_{vol} = N_{feed} \times ff_{vol} \tag{34}$$

where ff_{vol} is the feed fraction volatilized (39.6%), estimated based on average volatilization rates of composted organic waste materials (Sullivan, Bary et al. 2002).

The portion of undigested or egested nitrogen remaining once volatilization and consumption take place is also known as residue. This is calculated as follows:

$$N_{res} = N_{feed} - N_{BSF-bio} - N_{vol} \tag{35}$$

The resulting residue bioproduct from black soldier fly cultivation, N_{res}, is then recycled back into the nitrogen cycling in NoM as an input for Cropland in the Zone Urban Farm, offsetting a portion of the nitrogen fertilizer inputs to Cropland actors in the zone.

5.2.2.2 Constructed Wetlands: Assumptions and Constants

Leveraging Controlled-Environment Agriculture (CEA) strategies of water and nutrient recycling, vertically-stacked grow beds, and enclosed closed structure, a vertical constructed wetland (CW) (Figure 51) is used to upcycle nitrogen from wastewater treatment plant (WWTP) effluent before it is discharged to the environment.

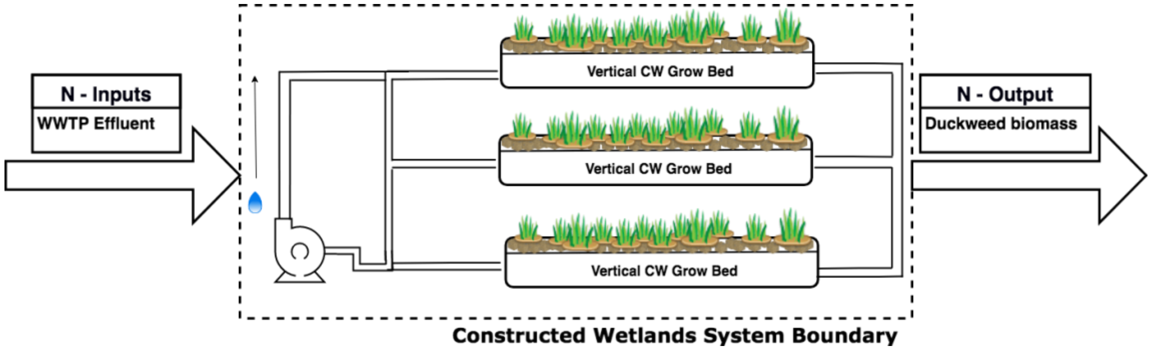


Figure 51: Constructed Wetlands schematic. Inputs of effluent from wastewater treatment plant (WWTP) that were previously discharged, land-applied, or recycled in the case studies presented in Experiment 1.

The total amount of duckweed biomass produced in the CWs is a function of available nitrogen in WWTP effluent. It is assumed that the nitrogen contents of this effluent are completely absorbed by the duckweed, and the areal requirement is dictated by the total mass of effluent nitrogen.

The duckweed grown in the CW accumulates nitrogen as it grows its own biomass and is then harvested for fish feed. Table 18 shows the parameters and the assumptions and constant values used to model the duckweed's nitrogen uptake, growth and nutritional value as a source of feed for the aquaponic fish.

Table 18: Constructed Wetland system assumptions and constants from literature

Abbreviation	Unit	Meaning	Value
N_{WWTP}	kg N day^{-1}	Total nitrogen influent (equal to WWTP effluent)	calculated
A_{CW}	m^2	CW area requirement to treat all wastewater effluent	calculated
$\mu_{A\text{-}CW}$	kg m^{-2} day^{-1}	Duckweed areal growth rate[1,2,3,4,5]	0.0143
NUR_{CW}	g kg^{-1} day^{-1}	CW N uptake rate[6]	0.803
$f_{CP\text{-}CW}$	% of DM	Crude protein content[1]	35

Table 18 (Continued)

$f_{N\text{-}CW}$	% of DM	N mass percent of biomass[1,7]	5.6
$N_{CW\text{-}bio}$	g N day^{-1}	Total N biomass production	calculated

[1] (Teles, Mohedano et al. 2017)
[2] (Cheng, Landesman et al. 2002)
[3] (Körner and Vermaat 1998)
[4] (El-Shafai, El-Gohary et al. 2007)
[5] (Zhang, Chen et al. 2014)
[6] (Iatrou, Stasinakis et al. 2015)
[7] (Nations 1977)

The nitrogen uptake rate, NUR_{CW}, is calculated based on growth rates taken from five experimental studies (Körner and Vermaat 1998, Cheng, Landesman et al. 2002, El-Shafai, El-Gohary et al. 2007, Teles, Mohedano et al. 2017), one of which found duckweed dry matter crude protein (Teles, Mohedano et al. 2017), along crude protein chemical composition also found in the literature (Nations 1977).

Using the growth rate per square meter and fraction crude protein, nitrogen uptake rate, NUR_{CW}, required to treat all wastewater effluent is calculated as follows:

$$NUR_{CW} = f_{Protein} \times f_{CP-CW} \times \mu_{A-CW} \tag{36}$$

where $f_{protein}$ is the fraction of nitrogen (16%) in crude protein by mass (Nations 1977), f_{CP-CW} is the fraction of crude protein (35%) contained in duckweed biomass and μ_{A-CW} is the average of experimentally-derived specific areal growth rate of duckweed (0.0143 kg per square meter per day) from several studies (Körner and Vermaat 1998, Cheng, Landesman et al. 2002, Zhang, Chen et al. 2014, Teles, Mohedano et al. 2017). The total nitrogen accumulated in duckweed biomass, N_{CW-bio}, is established using the following:

$$N_{CW-bio} = NUR_{CW} \times (WWTP\ effluent\ N) \tag{37}$$

where *NURcw* is the nitrogen uptake rate calculated above in Equation 34, and *WWTP effluent N* is the total amount of nitrogen released from the wastewater treatment plant (WWTP) in a given zone. (See Section 4.2.2.2 on page 87 for a description of how this value is calculated, and Appendix A for tabulated values.)

5.2.2.3 Aquaponics and Anaerobic Digesters: Assumptions and Constants

The next phase of the nutrient cycling module in the NoM experiment is the aquaponic system. This is another Controlled-Environment Agriculture (CEA) system with several sub-components, including fish tanks, hydroponic crops, and two anaerobic digesters that provide electricity for the system's pumps. The schematic of this system can be found in Figure 52.

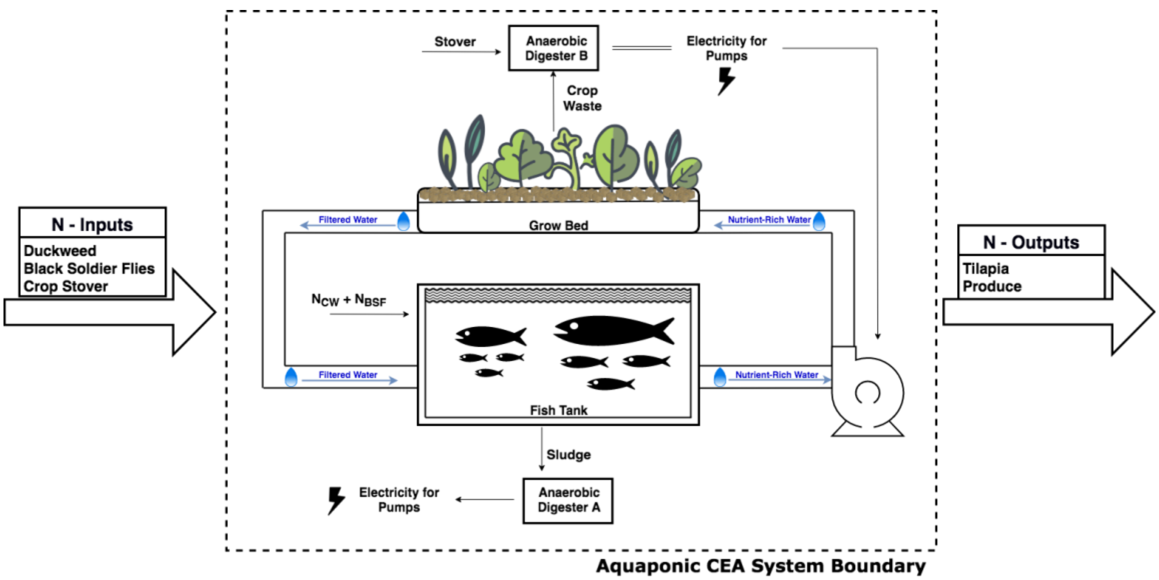


Figure 52: Aquaponic system schematic, including plants, fish, and anaerobic digesters.

Table 19 provides an overview of the aquaponic system and included assumptions.

Table 19: Aquaponic system assumptions and constants.

Abbreviation	Unit	Meaning	Value
$N_{feed\text{-}AP}$	kg N day^{-1}	N flux through fish feed	calculated
$R_{feed\text{-}AP}$	kg (kg fish)$^{-1}$	Feed to biomass ratio[1,2,3]	2
N_{fish}	kg N day^{-1}	N in fish biomass[1,2,6]	calculated
ff_{sludge}	% of feed N	N relegated to sludge[1]	2
NAR_{plant}	% of feed N	N assimilation ratio by plant biomass[1]	6
NDR	% of feed N	N removal ratio by denitrification[2,4]	45
NE_{fish}	% of feed N	Nitrogen accumulation in fish[2]	45
FCR_{fish}	kg (kg fish)$^{-1}$	Feed conversion ratio for fish[1,3]	1.4
N_{plants}	% of dry matter	Plants N content[1,2,6]	calculated
f_{IE}	%	Inedible plant biomass yield[7]	50
f_E	%	Edible plant biomass yield[7]	50

[1] (Trang and Brix 2014)
[2] (Bugbee 2004)
[3] (Hindelang, Gheewala et al. 2014)
[4] (Iatrou, Stasinakis et al. 2015)
[5] (Love, Fry et al. 2014)
[6] (Cease, Capps et al. 2015)
[7] (McCoy 2013)

The total feed nitrogen used to cultivate aquaponic fish is calculated from the total biomass N grown in the BSF and CW components:

$$N_{feed-AP} = N_{BSF-bio} + N_{CW-bio} \tag{38}$$

Because aquaponic fish are reared entirely on black soldier fly larvae and duckweed grown in the constructed wetlands, by extension, the total aquaponic productivity depends entirely on the wastewater nitrogen and food waste solids.

The Aquaponic fish had an N uptake rate that is derived from the following equations:

$$NAR_{fish} = N_{feed-AP} \times NE_{fish} \tag{39}$$

$$N_{sludge} = N_{feed-AP} \times ff_{sludge} \tag{40}$$

This study leverages the general schematic and model assumptions outlined in the literature (Yogev, Barnes et al. 2016) in which an anaerobic digestion process converts organic carbon to biogas so energy can be recovered for pump power. These researchers found that with a fish standing stock of about 700 kg would produce 3.4 tons of fish annually and enough nutrients to grow about 35 tons of tomatoes per year (chosen as a model plant) and recover sufficient energy (70 kWh/day) to run the system on biogas.

While this model is selected in this study for its energy assumptions, the Yogev, Barnes et al. (2016) model assumes perfect assimilation of nutrient, which is not corroborated in other aquaponic studies. Thus, the nutrient assimilation and growth assumptions were derived from experimental studies that tracked nitrogen mass flow (Bugbee 2004, Hindelang, Gheewala et al. 2014, Trang and Brix 2014, Iatrou, Stasinakis et al. 2015). The model assumes that there is a direct correlation between the amount of applied feed and waste produced, and consequently the amount of energy created by biogas production. By upscaling the system size, it is expected to reduce the energy demand per kilogram of fish produced (Yogev, Barnes et al. 2016). This is due to economies of scale in recirculating pumps and blowers, where increasing size is related to increased efficiency.

5.2.3 Network Construction

The fifth and final case study presented in this thesis, the Nutrient Optimizing Module (NoM) case, is based on the construction of the Zone Urban Farm (ZUF – case 2) network from the first experiment, outlined in the Materials and Methods section in the previous chapter, (4.2) in the Agri-Network Centralization Experiment (ACE). The NoM actors are only introduced in the zones, and thus all of the modifications made to connectivity in the NoM case only occur within these zones, with the exception of the removal of the Municipal Solid Waste (MSW) actors from the county levels in the ZUF. The new zone level connectivity is pictured in Figure 53 and contextualized as a modification of the Zone Urban Farm case study in Figure 54. (Refer to Figure 19 on page 101 for ZUF constant actors and flows.)

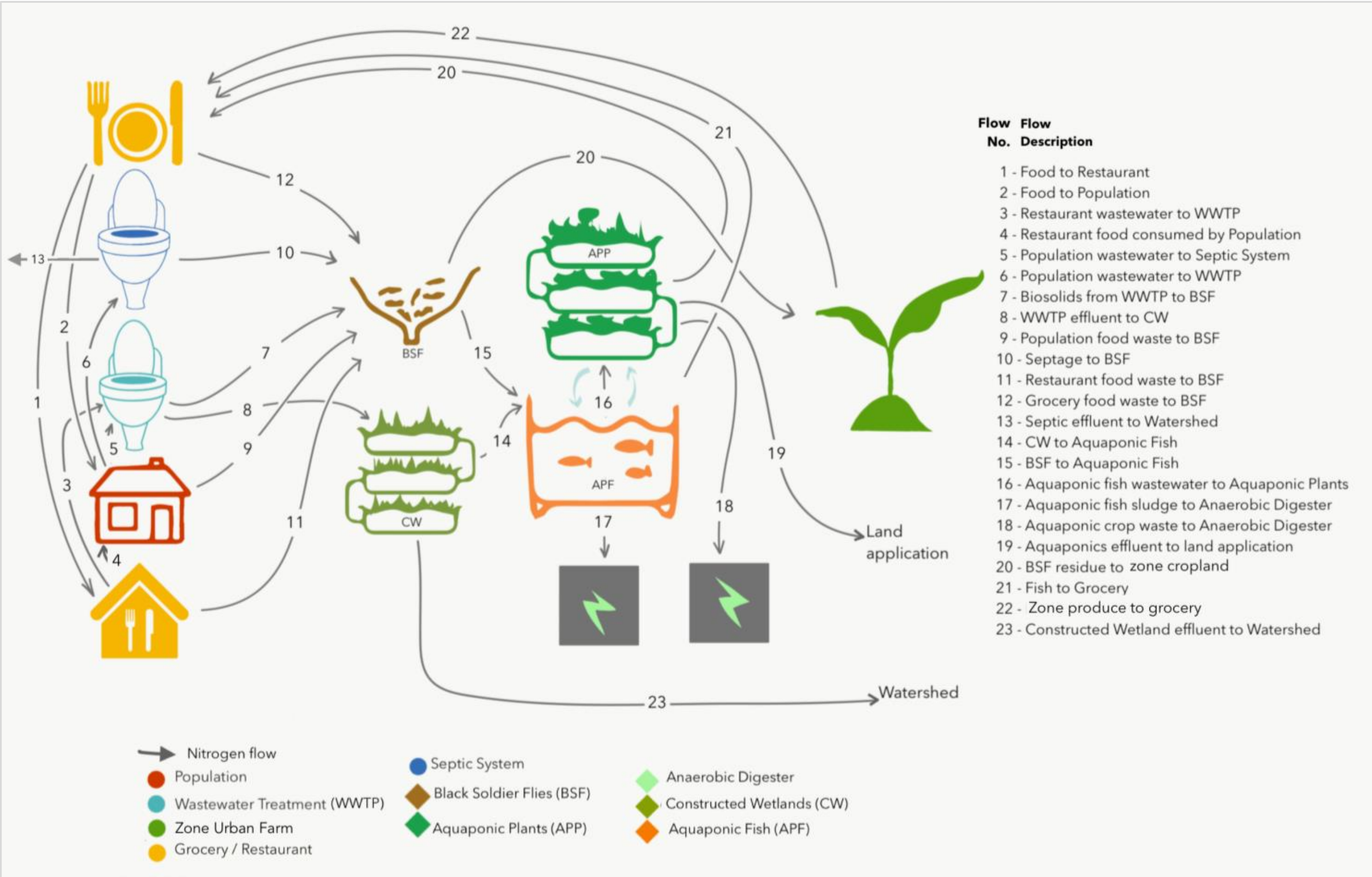


Figure 53: Case Study 5 network construction at the zone level. Farm, Poultry, and Food Distributor actors are connected in the same way as Case 2 (Zone Urban Farm Case) from Experiment 1 (Agri-Network Centralization Experiment). Any excess BSF residue (flow 2) or Aquaponic effluent (flow 19) is exported from the system.

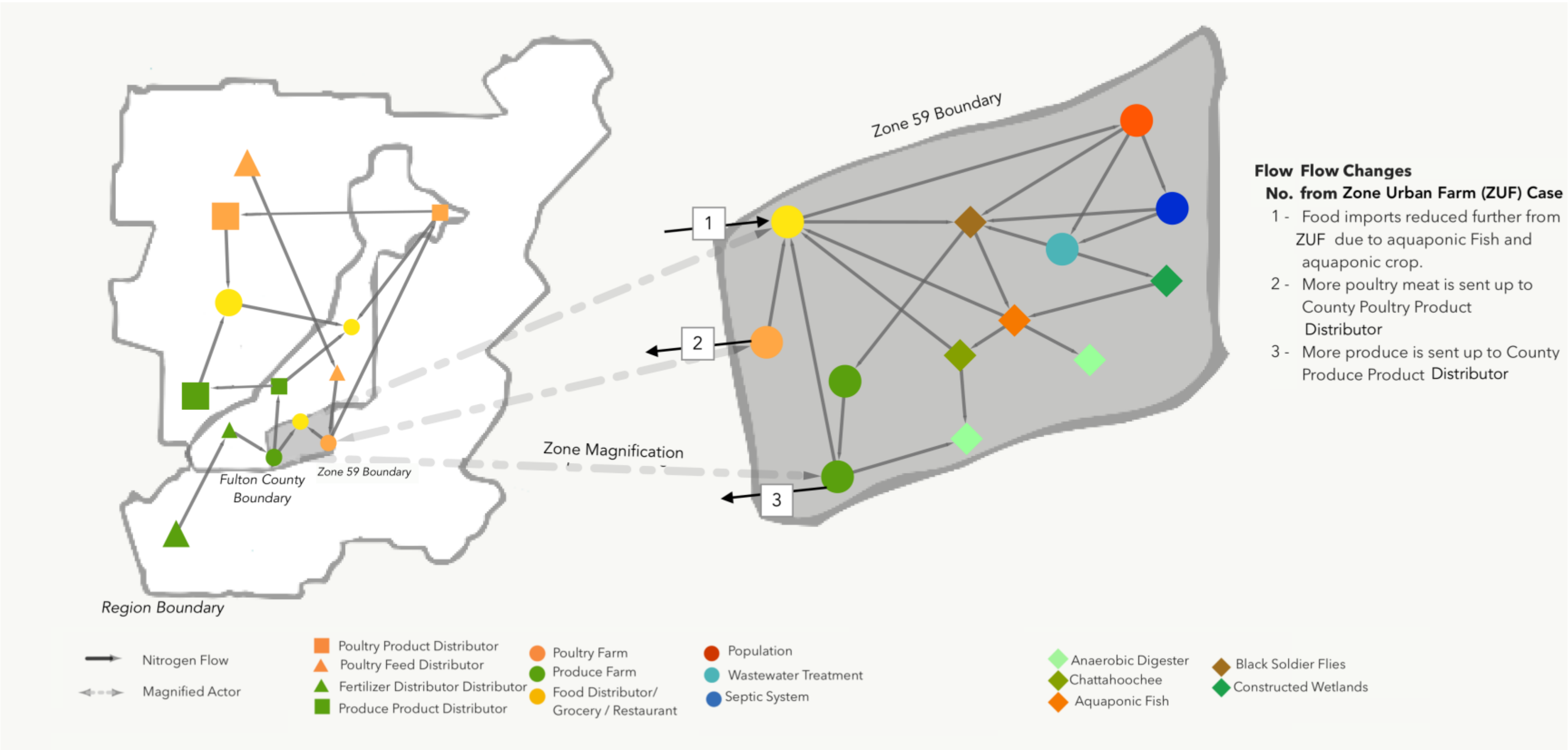


Figure 54: Contextualizing the addition of the NoM actors into the Zone Urban Farm case study to form the NoM case (case study 5

5.2.4 Analysis of Case Study

Following the construction of each network case study (Tasks 2a-b), the fifth case study is then analysed in a similar manner as the Agri-Network Centralization Experiment (ACE) case studies from the first experiment (see 4.2). The NoM case study is analysed with respect to its input flows, internal flows, exports, and waste flows, as well as its network structure and flow metrics using methods outlined in the Ecological Network Analysis section in Section 3.1. Next, imports, exports and waste flows are then compared between the NoM case, the baseline, and the urban farm scenario to illustrate the relative changes to environmental impacts from food miles brought on by a shift to urban agriculture food procurement with enhanced nutrient cycling.

5.2.4.1 <u>Network Analysis</u>

First, the ecological network metrics are determined for the NoM case study using the following steps:

1. Flows of waste nitrogen from wastewater treatment, population, restaurant, and grocery actors to each biotechnology actor are tabulated in excel.
2. Nitrogen assimilation and efficiencies for each actor are used to determine biomass and associated waste production in each zone.
3. Production of aquaponic fish and plant biomass are used to calculate offset food requirement in each zone, and production of black soldier fly larvae residue is used to calculate offset fertilizer requirement in each zone, and these are tabulated in excel.

4. Using MATLAB, the excel spreadsheet is converted into N+3 x N+3 formatted array with N actors and their corresponding flow values, to which imports, row 0, and exports and dissipation (rows N+1 and N+2, respectively) are added, as described in Section 3.1.2.
5. The corresponding "flow matrix" produced is then converted into an adjacency matrix, or "structure matrix," with 1's replacing any weighted values.
6. Using the Ecological Network Analysis (ENA) methods described in Chapter 3, both structure and flow metrics are calculated for the NoM case study using the "flow" and "structure" matrices.
   a. Twelve ecological structure metrics are calculated: Species Richness (n), Number Of Links (L), Connectance (C), Linkage Density (L_D), Prey (n_{prey}), Predators ($n_{predator}$), Prey-Predator Ratio (P_R), Number of Specialized Predators ($n_{s\text{-}Predator}$), Fraction of Specialized Predators (P_S), Vulnerability (V), Generalization (G), and Cyclicity (λ_{max}).
   b. Nine ecological flow metrics are calculated: Finn's Cycling Index (*FCI*), Mean Path Length (*MPL*), Average Mutual Information (*AMI*), Ascendency (*ASC*), Development Capacity (*DC*), Total System Overhead (*TSO*), Total System Throughflow (*TST*), *ASC/DC*, and Robustness (*R*).

Following the computation of ENA metrics, the structure matrix found in step (2) above is used to determine the structural centralization te NoM network. Centralization is calculated using the relationship between centrality of each actor, as described in Section 3.2. Given the size of the network, the opensource software environment known as Cytoscape is used to perform this task (Freeman 1978, Shannon, Markiel et al. 2003).

Next, Using the ENA metrics calculated for the NoM network, the ENA metrics are compared to existing food web median values (Borrett Stuart and Lau Matthew 2014, Layton 2014). The NoM case study is then compared to the urban farm and baseline case studies.

5.2.4.2 Quantification of Food Miles Reduction from Urban Agriculture

Following determination of flows into the NoM network, an LCA is conducted using similar methods described in Section 4.2.5.2 and food miles are evaluated for the urban farm case studies from the Agri-Network Centralization Experiment and the NoM network case studies. The LCA uses SimaPro 8.2.3, leveraging inventory data from Agri-Footprint 3.0, Ecoinvent 3, Industry Data 2.0, and USLCI using the locations from Section 4.2.5.2. and their distances from the Atlanta Metropolitan Region. The total weights of each of the food products and the magnitudes imported in the NoM case study is compared to the baseline and urban farm scenarios, and LCA impacts are calculated using ReCiPe's (H) 2016 endpoint assessment.

5.3 Results and Discussion

Upon completion of the research tasks outlined in Section 5.2, the Nutrient Optimizing Module (NoM) experiment is analysed first for its ecological network metrics, both with and without the basin actors. Next it is compared to the baseline and urban farm scenario case study results presented in Section 4.3 in order to contextualize the NoM case study within the urban agriculture landscape. These case studies are all compared using centralization, ENA, and flow magnitudes to evaluate changes to network performance and food mile impacts. They are also examined with respect to natural food web median values from literature in order to benchmark ways in which the NoM actors change the network within the ecological context (Borrett Stuart and Lau Matthew 2014, Layton 2014).

5.3.1 Network Analysis Results

Ecological network analysis (ENA) is performed using the methods outlined in 3.1 to analyse the Nutrient Optimizing Module (NoM) case study with respect to ecological network performance. This section presents the ENA and Centralization results of this analysis, both with and without the inclusion of Basin actors in the NoM network.

ENA structure-based metrics are found first, using the calculations described in Section 3.1.1. The results of this analysis are presented in Table 20.

Table 20: ENA Structure metric results for the Nutrient Optimizing Module (NoM) network, with (+) and without (-) basin actors.

Case Study	n	L	L_D	C	n_{Prey}	$n_{Predator}$	P_R	λ_{max}	$n_{s\text{-}predator}$	P_s	V	G
5 – NoM+	1405	3575	2.544	0.002	1279	1280	0.999	2.09	693	0.541	2.80	2.79
5 – NoM-	1400	3398	2.427	0.002	1274	1275	0.999	2.09	693	0.544	2.67	2.67

NoM+ - Nutrient Optimizing Module with Basin actors
NoM- - Nutrient Optimizing Module without Basin actors

N – number of species (species richness)
L – number of links

LD – linkage density
C – connectance
PR – prey to predator ratio
λmax – cyclicity
Ns-pred. – number of specialized predators
V – vulnerability
G - generalization

The results of the flow analysis, calculated for the NoM network case study using formulas outlined in Section 3.1.2, can be found in Table 21.

Table 21: ENA Flow metric results for the Nutrient Optimizing Module (NoM) network, with and without Basin actors.

Case Study	*FCI*	*MPL*	*AMI*	*ASC*	*DC*	*TSO*	*TST*	*ASC/ DC*	*R*
5 – NoM_{+}	0.052	6.23	5.80	1.68 x10^{9}	2.54 x10^{9}	8.58 x10^{8}	2.50 x10^{8}	0.66	0.39
5 – NoM_{-}	0.054	5.98	5.76	1.61 x10^{9}	2.45 x10^{9}	8.41 x10^{8}	2.40 x10^{8}	0.657	0.398

NoM+ – Nutrient Optimizing Module with Basin actors
NoM- – Nutrient Optimizing Module without Basin actors

FCI – Finn's Cycling Index
MPL – Mean Path Length
AMI – Average Mutual Information
ASC – Ascendancy
DC – Development Capacity
TSO – Total System Overhead
TST – Total System Throughflow
R - Robustness

These results are discussed alongside the results of the Agri-Network Centralization Experiment and natural food web medians from literature (Borrett Stuart and Lau Matthew 2014, Layton 2014) in Sections 5.3.3 and 5.3.4.

5.3.2 Imports, Exports and Waste in the NoM Case Study

The following section provides an overview of the food, waste, and cycling produced though incorporation of the NoM biotechnology actors.

5.3.2.1 Food Production in the NoM Case Study

Food production in the region is increased through use of Aquaponics at the zone level. This food further offsets the amount of food imports required for the population. The aquaponics systems have associated nitrogen products and wastes, which are outlined in Section 5.2.2. Figure 55 provides visualization of all the food production in each of the counties in the NoM case study.

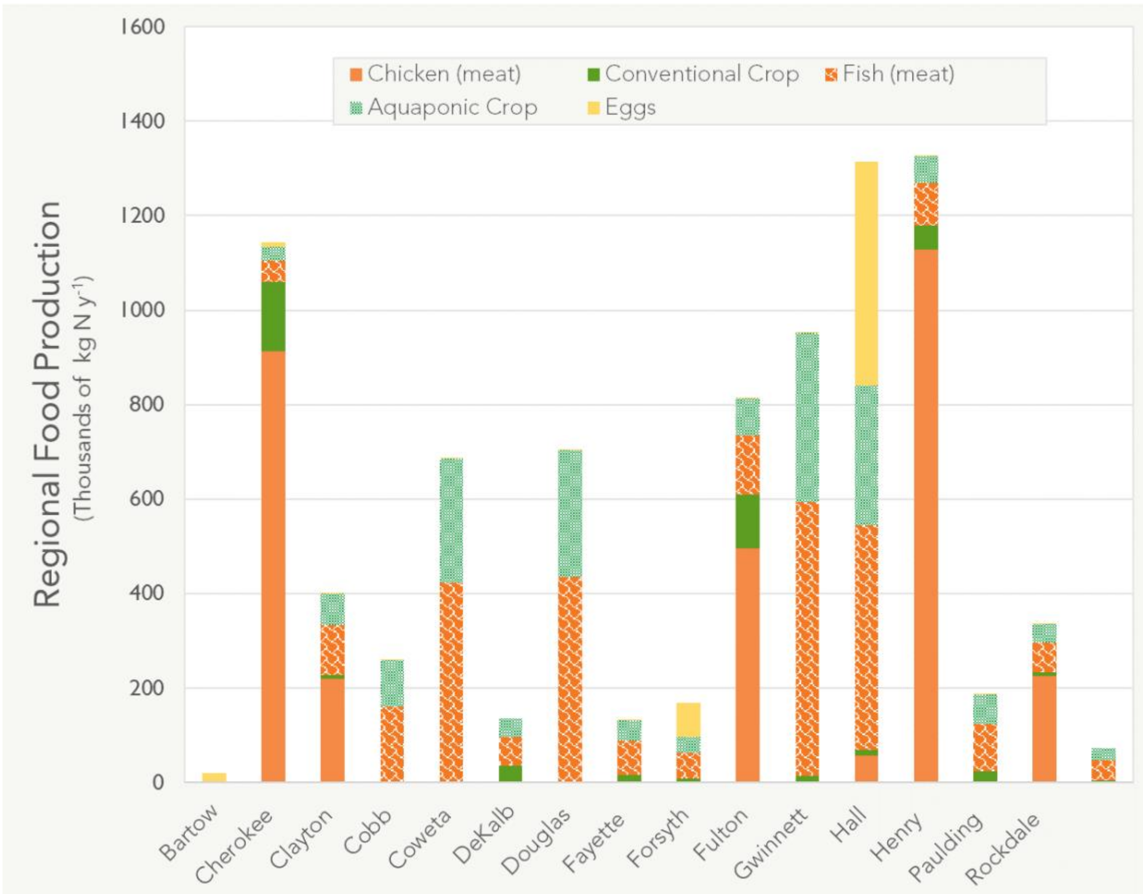


Figure 55: Food production by county and type in the NoM case study.

Conventional crop, egg, and poultry totals do not change between the NoM case study and the case studies presented in the Agri-Network Centralization Experiment (ACE) presented in Section 4.3. However, additional fish and aquaponic crop products enable increased urban self-sufficiency. The total aquaponic productivity is almost entirely inversely correlated to the food produced in the original urban farm networks. This is because, as stated previously, the amount of aquaponic productivity depends entirely on the presence of waste from food and wastewater treatment processes. As mentioned in Section 2.2, this increased self-sufficiency in turn serves to increase the "Development" of the urban food system by reducing the required imports to the system. The county-level increases are discussed in further depth in Section 5.3.3 when the NoM case study is contextualized alongside the case studies presented in the Agri-Network Centralization Experiment (ACE) from Chapter 4.

5.3.2.2 Case Studies Compared

At times it can be difficult to decide whether a product should be sent to “dissipation” or “exports.” In all 4 Agri-Network Centralization Experiment (ACE) case studies, there is a large amount of recoverable waste nitrogen produced in both the food and wastewater management sectors, and this must be allocated based on the designer’s understanding of the system and their down-stream uses. Figure 56 shows the relative flow magnitudes for the imports, internal flows, exports, and dissipation for the 5 case studies.

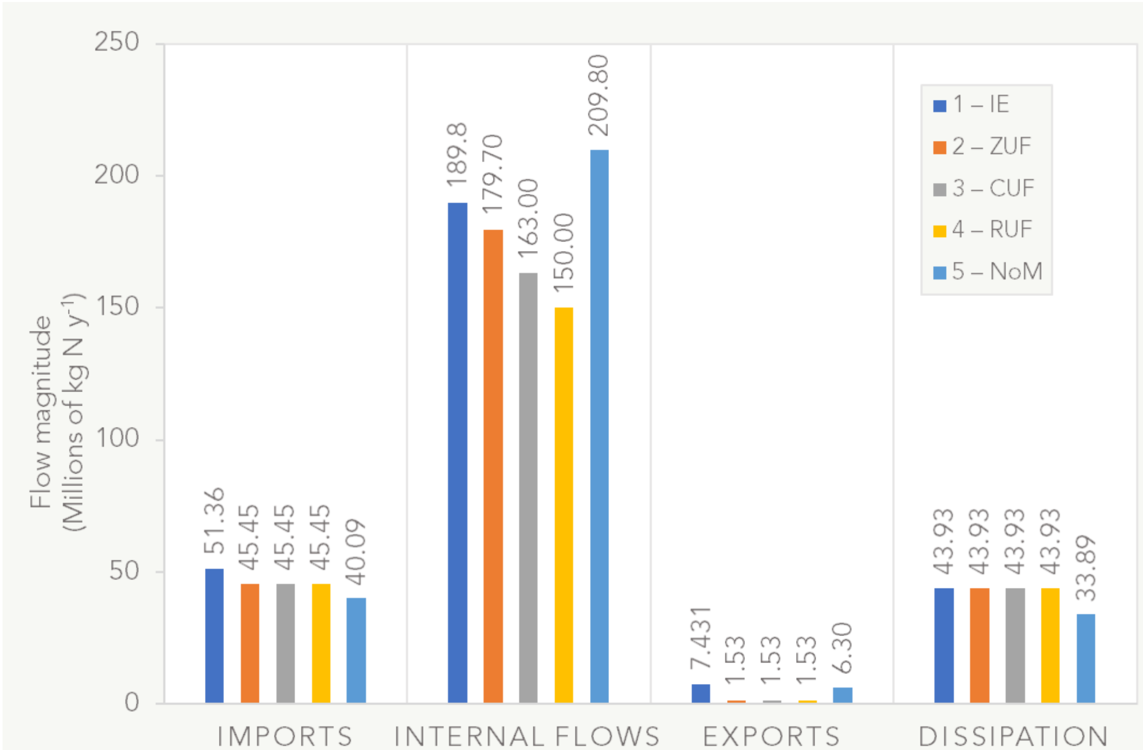


Figure 56: Imports, exports, and dissipation flow magnitudes compared the between all 5 case studies with Basin actors removed.

In the NoM case study there is a drastic increase in the internal flows. As per the impact discussion posed in Section 4.4, the increased mediations illustrated by this change may lead to increased environmental burdens of material handling, transportation, and losses. However, the NoM was designed to bring the material cycling close to the source of waste material, at the wastewater treatment plants, in the case of effluent and biosolids, and within the zone, as opposed to solid waste municipalities that haul solids out of counties to neighboring landfills. In this respect, colocation of the NoM modules near the source of waste and near the consumers may lessen or negate this potential downside.

This chart makes evident the impact of the NoM modules on imported flows. In Section 4.3.3 it was demonstrated that the urban farm scenario could decrease food imports by 10% from the baseline. When aquaponics is introduced to augment the urban farm scenario presented by the Zone Urban Farm case, there is an additional 15% of reduction in the required food imports to the region from the urban farm scenario value. Food production changes afforded by the NoM urban agriculture augmentation can be seen in Figure 57.

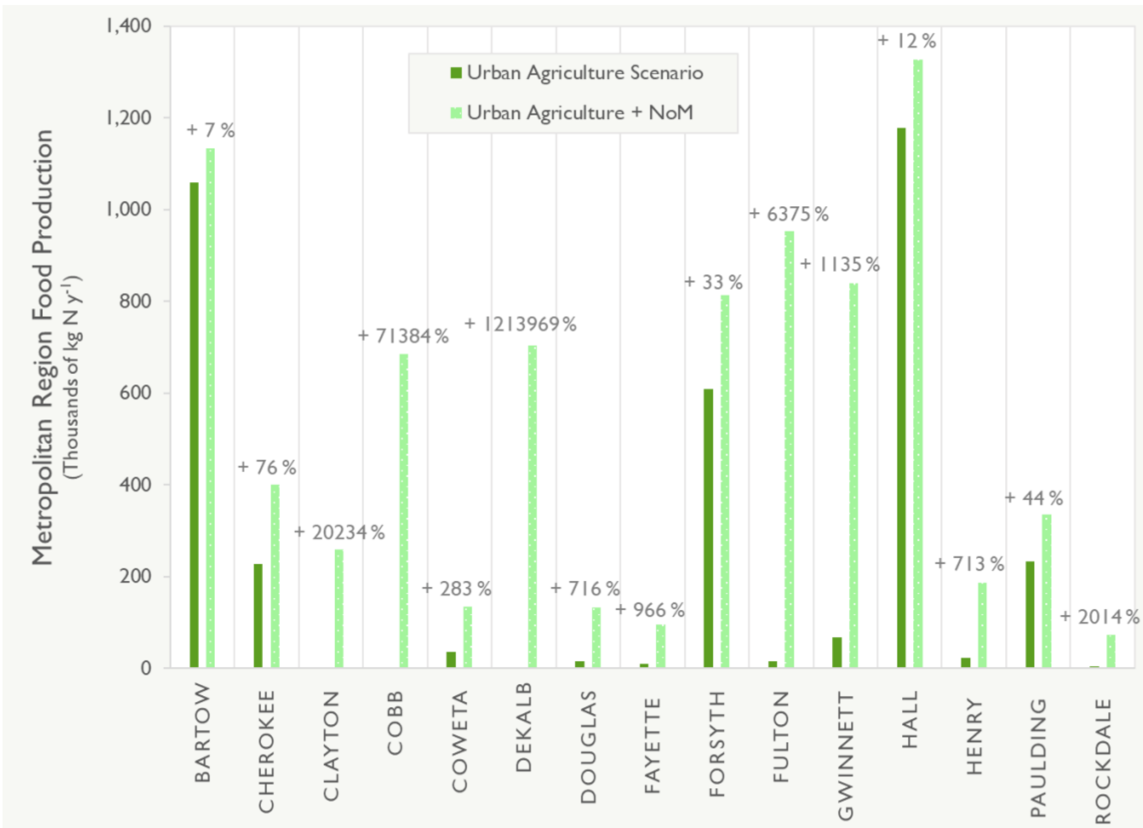


Figure 57: Food grown within the system before and after Nutrient Optimizing Modules are added. Portion of food requirement grown in the Region before module (10%) and after (23%).

Using the remainder of food imported to the region in both the urban farm scenario (see Section 4.3.3 on page 126) and in the NoM case study shown above, an impact assessment is then conducted using the relative food miles required to supply food to the Atlanta Metropolitan Region population for the revised urban farm scenario that includes

NoM modules. As described previously, the values of the top 5 national food producers and their relative proportions of the total magnitude of national product flows are used to determine food miles traveled and proportion of imported food to the region (see Section 4.2.5.2).

The results of the Food Miles LCA, comparing the urban farm scenario with the NoM case study can be found in Table 22.

Table 22: Life Cycle Impact Assessment Characterization of Nutrient Optimizing Module Case import food miles compared to the urban farm scenario food miles.

Impact category	Unit	Urban Farm Scenario (Agri-Network Centralization Experiment)	Nutrient Optimizing Module Experiment
Global warming, Human health	DALY	1134.04	1334.16
Global warming, Terrestrial ecosystems	species.yr	3.422	4.026
Global warming, Freshwater ecosystems	species.yr	9.35E-05	1.10E-04
Stratospheric ozone depletion	DALY	0.433	0.509
Ionizing radiation	DALY	-0.075	-0.088
Ozone formation, Human health	DALY	3.195	3.758
Fine particulate matter formation	DALY	827.4	973.5
Ozone formation, Terrestrial ecosystems	species.yr	0.463	0.545
Terrestrial acidification	species.yr	0.564	0.664
Freshwater eutrophication	species.yr	0.181	0.213
Terrestrial ecotoxicity	species.yr	0.132	0.155
Freshwater ecotoxicity	species.yr	0.011	0.013
Marine ecotoxicity	species.yr	0.003	0.003

Table 22 (Continued)

Human carcinogenic toxicity	DALY	131.5	154.7
Human non-carcinogenic toxicity	DALY	144.4	169.9
Land use	species.yr	0.740	0.870
Mineral resource scarcity	USD2013	516100	607200
Fossil resource scarcity	USD2013	161144500	189581700
Water consumption, Human health	DALY	17	20
Water consumption, Terrestrial ecosystem	species.yr	0.101	0.118
Water consumption, Aquatic ecosystems	species.yr	4.50E-06	5.29E-06

Results suggest that $91 Thousand can be saved in the mineral resource scarcity category, and $24.5 Million in fossil resources can be spared through the additional 15% reduction in food miles afforded through aquaponic food production within the system boundary.

It was also determined that fertilizer imports to the system could be reduced by over 31% by simply retaining black soldier fly residues in the zone and exporting surplus. This will be explored in more depth in Section 5.3.4.

In addition to benefits afforded by reducing the imports to the system, the nutrient modules recycle much of the nitrogen that would otherwise be sent to the neighboring watershed as wastewater effluent and biosolids, regardless of whether or not basins are included as designated actors in the system. Figure 58 shows the total magnitude of nitrogen that is released to the 5 watersheds in the baseline and NoM configurations, along with the reduction percentages in each.

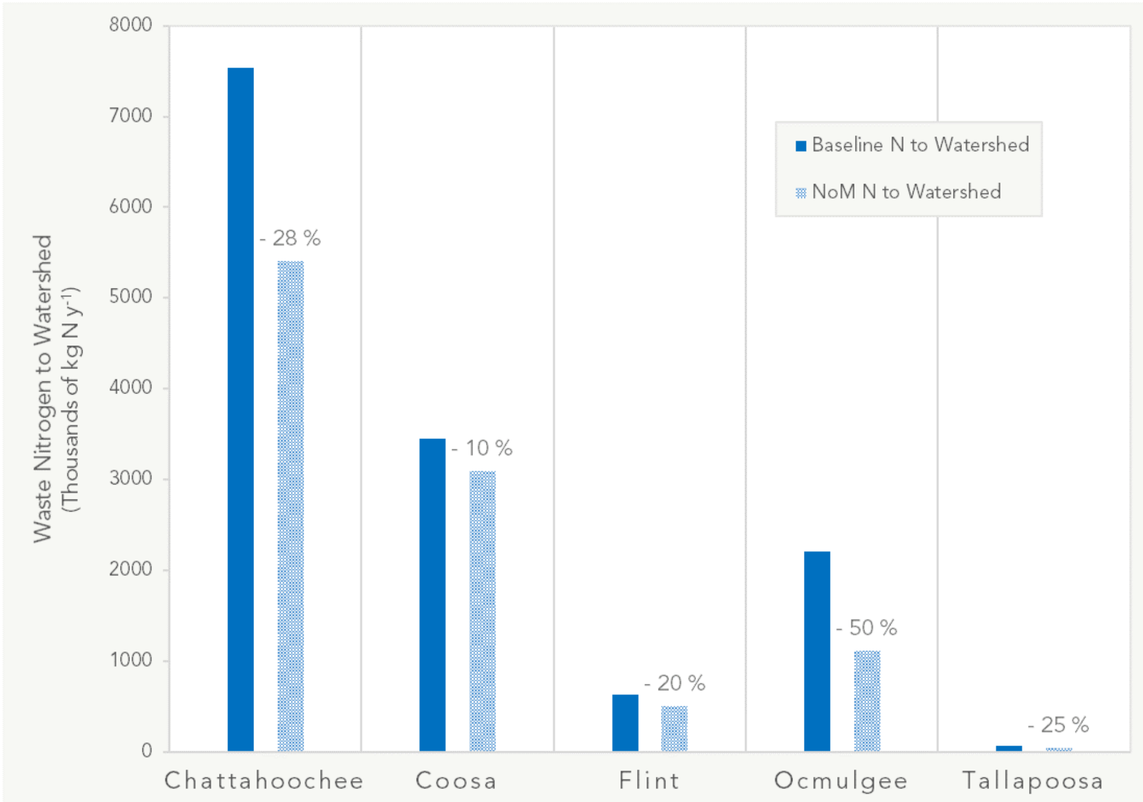


Figure 58: Nitrogen emissions released to receiving basins in the NoM case compared to the Agri-Network Centralization Experiment (baseline and urban farm case studies). Results are given in thousands of kilograms of nitrogen per year.

Chattahoochee experience the greatest reduction by magnitude, but this is only because this is the watershed that receives the highest percent of all flows. The greatest beneficiary by percentage is Ocmulgee, which sees a 50% reduction in N flow to the watershed through the diversion of effluent from wastewater treatment operations into the NoM biotechnology actors. This difference is accounted for by the fact that NoM waste reduction is magnified by population densities. Recall, the total emissions to watershed remains constant in the farm actors between the ACE case studies and the NoM. However, it is the effluents to the watershed originating in wastewater treatment facilities where the NoM derives its benefit. Thus, the watersheds that receive proportionally more effluent nitrogen from wastewater treatment, as compared to farm runoff, receive the greater benefit. For this reason, Coosa, which serves as the receiving basin for less densely populated regions with proportionally more farm production, receives the smallest benefit to watershed emissions.

Figure 59 breaks down the total waste nitrogen produced as a result of food consumption activities, such as uneaten or spoiled food waste as well as metabolic waste products flushed to the wastewater treatment sectors.

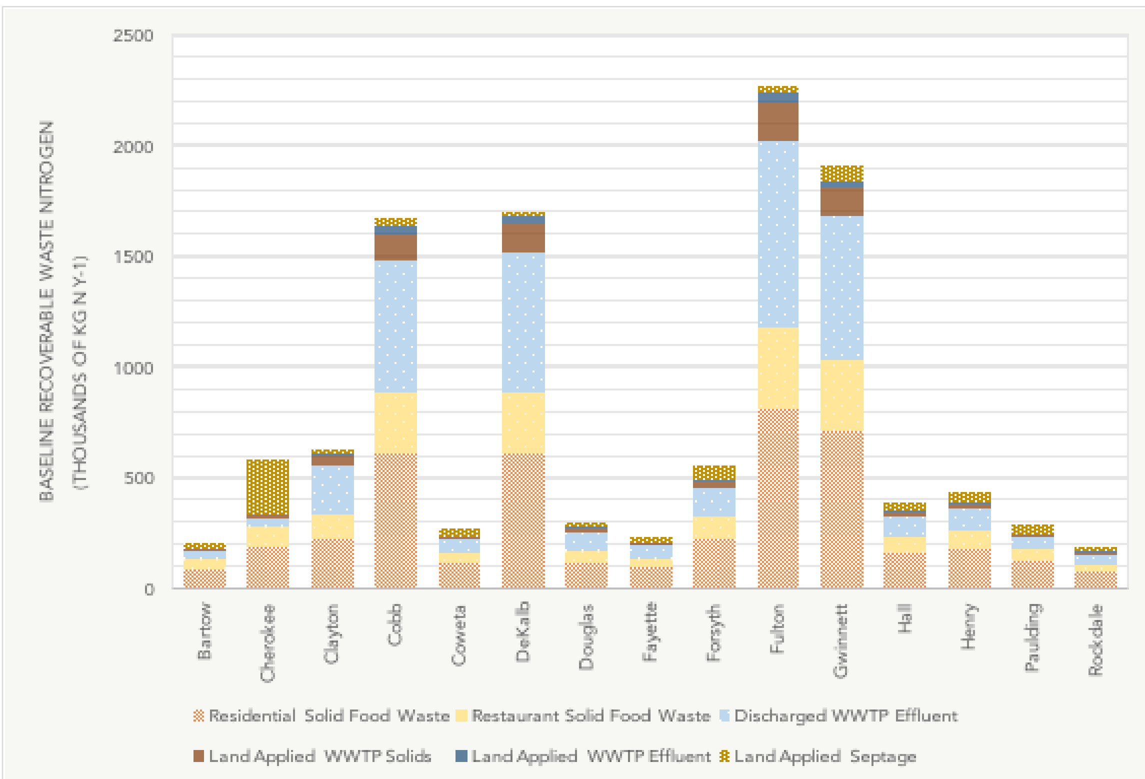


Figure 59: Recoverable wastes produced in ACE case studies.

The data represented in Figure 60 illustrate all of the inputs to the NoM biotechnology modules. Comparatively, the waste products resulting from the NoM are pictured to emphasize the reduction in nitrogen inefficiency afforded by the NoM modules.

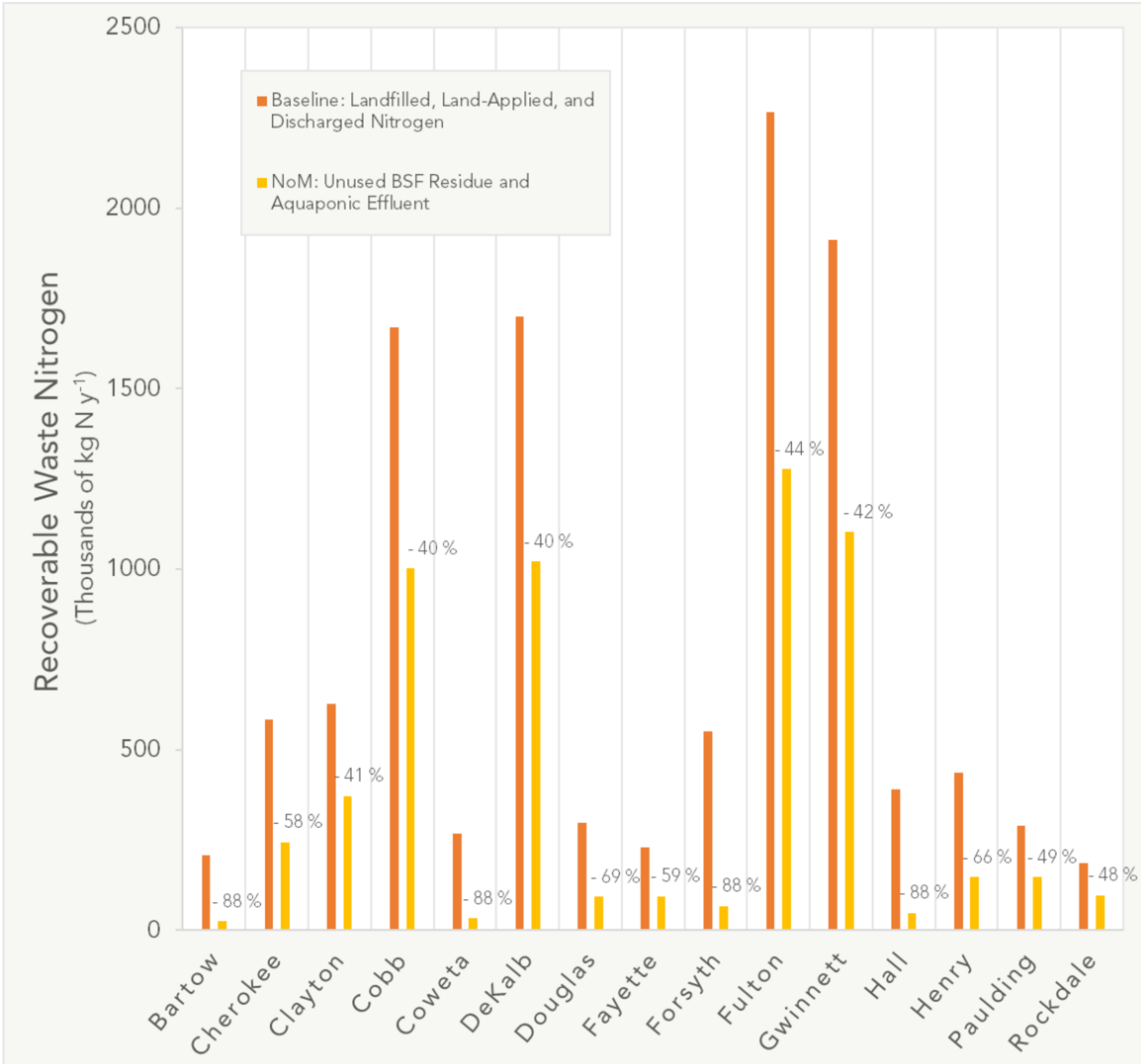


Figure 60: Reduction in recoverable food and water waste products produced in the NoM case study (black soldier fly residue and aquaponic effluent) as compared to the baseline (wastewater treatment effluents and solids, food waste, and septage).

Literature indicates that wastewater treatment effluents overload the Chattahoochee watershed (Calhoun, Frick et al. 2003, Frick, Zaugg et al. 2003, Walker and Beck 2011). As exact ecosystem data for locations of the applied biosolids and effluent is not publicly available, further analysis will require that assumptions be made regarding ecosystem services provided by this practice and the changes induced by aquaponics. Alternatively, additional crop area could be constructed to absorb the excess nutrient in order to more fully leverage the nutrient cycling afforded by the NoM systems. If more aquaponic crop area were incorporated into the model to leverage the aquaponic effluent, the food production capacity would increase in the Region. These limitations of the NoM model are discussed in Section 5.3.4.

5.3.2.3 Nutrient Cycling

The increased urban self-sufficiency afforded by the NoM case study is due to the cycling and additional food production capacity introduced by the biotechnology modules.

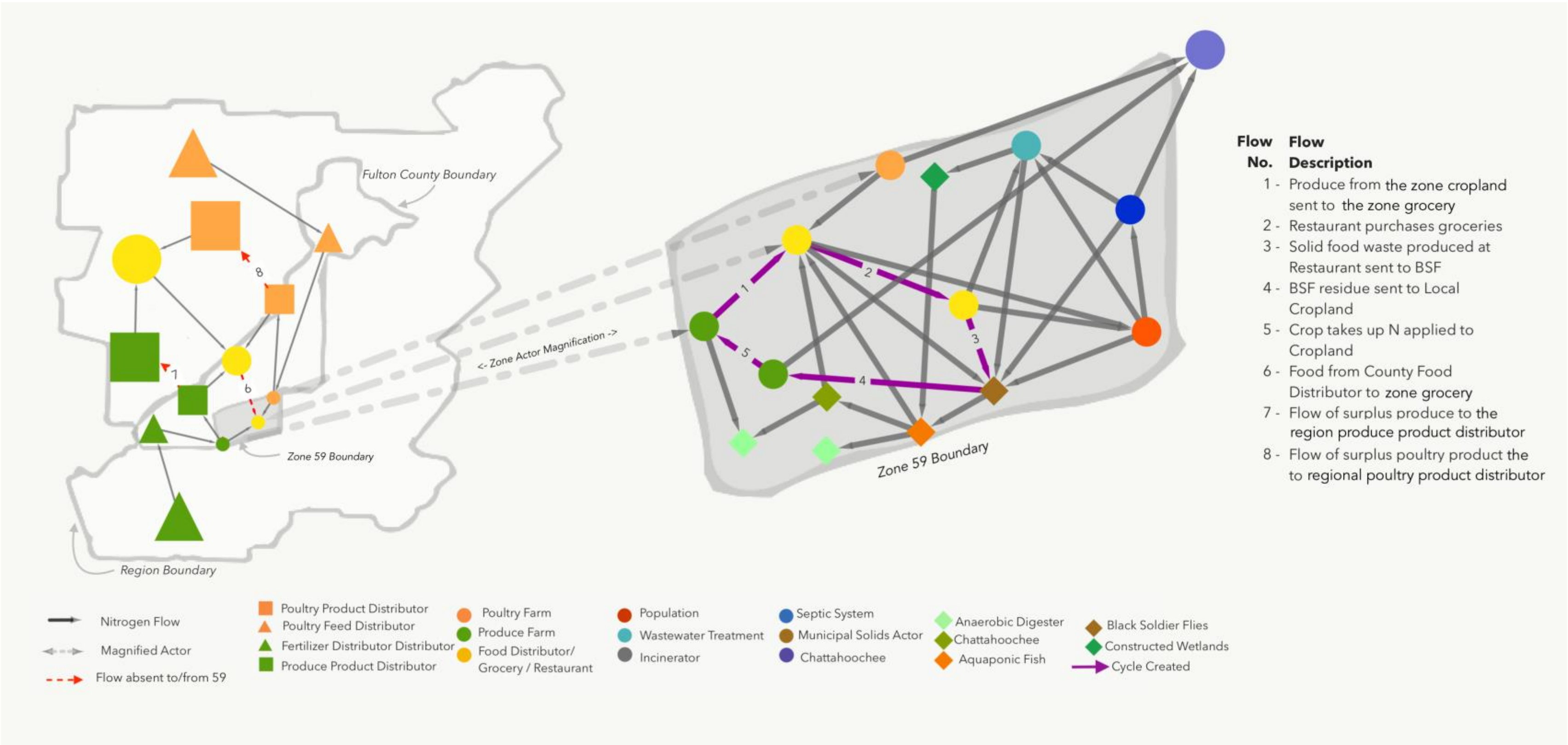


Figure 61: NoM case study magnified to zone 59 in Fulton County. An example of a cycle created by the introduction of NoM is highlighted (purple). Crop grown within the zone is sent to the zone grocery (flow 1), followed by the zone restaurant (flow 2), whose waste goes to the black soldier fly (BSF) module (flow 3). BSF residue nitrogen is recycled back to the zone cropland (4) as soil conditioner and finally to the harvested crop (flow 5). The red dashed lines indicate flow is absent to zone 59 from the Fulton County Food Distributor (flow 6), from the Fulton County produce product distributor (flow 7) and the county poultry Product distributor (flow 8) to the Region distributor.

An example of a cycle in the Nutrient Optimizing Module Case Study is highlighted purple. In this highlighted cycle, Crop grown at the zone-level cropland is sent to the zone grocery (flow 1). This produce is then purchased for consumption at the zone restaurant (flow 2). Nitrogen from solid food waste uneaten at this restaurant are then sent to the black soldier fly (BSF) module (flow 3) for consumption by larvae. The unassimilated BSF residue nitrogen is then recycled back to the zone farm (flow 4) as soil conditioner, where nitrogen finally is absorbed by the harvested crop (flow 5).

Also visible in Figure 61 are the red dashed lines indicating flows that are absent in this zone and county. Because of the increased zone food production afforded by produce and fish from the Aquaponics module, when added to the locally grown produce and poultry, zone food is able to completely supplant flows from the County Food Distributor.

5.3.2.4 New Waste Streams and Land Use Requirements

The NoM model was constructed with the assumption that only a portion of the potential cycling would occur. The model builds in losses due to volatilization and imperfect aquaponic plant nutrient recovery reported in experimental literature (see 5.2.2). The unrecoverable losses, such as volatilization, are treated as dissipated flows. Additionally, as the model was constructed with the objective of maximizing decentralized cycling, excess recoverable wastes are not sent up the hierarchy for redistribution, but are instead exported from the system. These include aquaponic effluents and surplus soil conditioner produced by black soldier fly larvae.

Figure 62 provides a visualization of the county totals of aquaponic fish, crop, and associated nitrogen waste flows in the Nutrient Optimizing Module (NoM) case study.

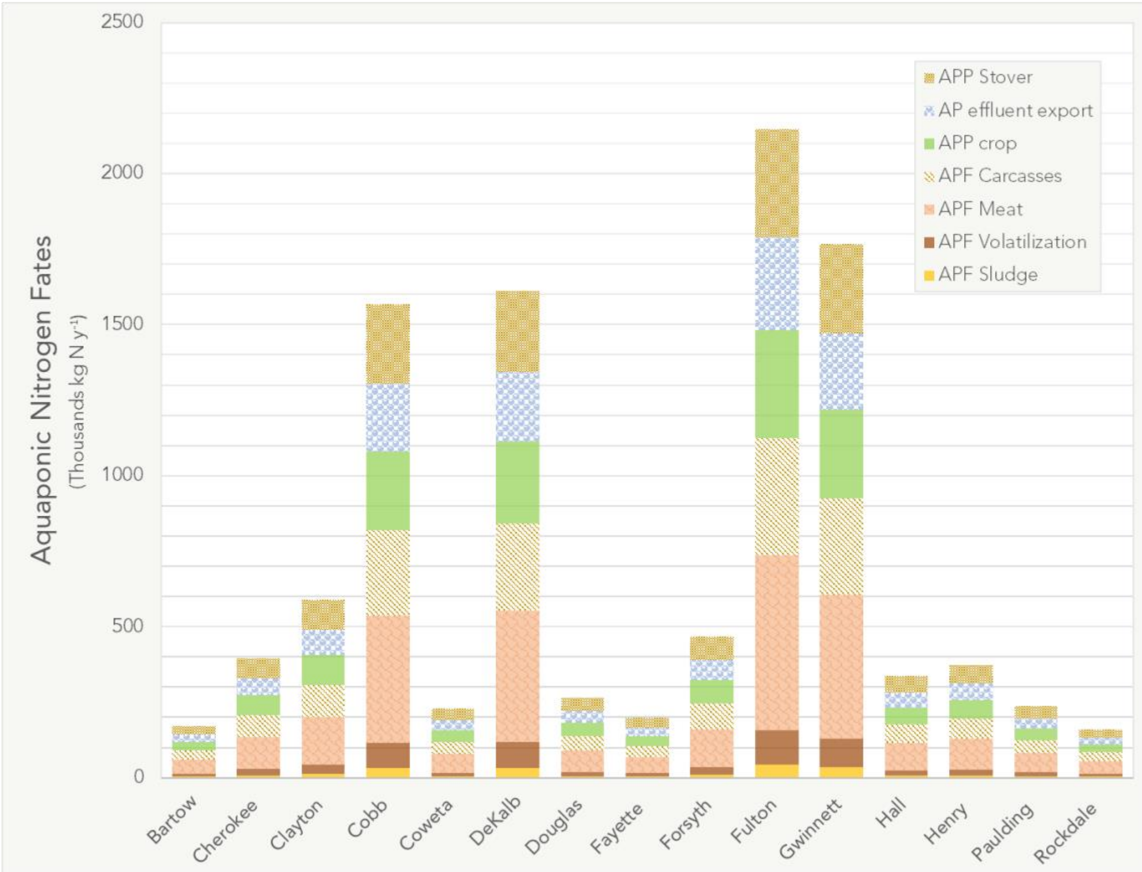


Figure 62: Aquaponic fish, crop, and associated nitrogen flows in the NoM network.

As can be seen Figure 62, a large portion of the nitrogen products from the aquaponic system are wastes. These include: 50% of the plant biomass, which is inedible crop stover, which can be used for biogas production or composted for soil conditioner; 30% of the aquaponic fish effluent nitrogen, which could be recirculated to grow additional crop or applied to organic cropland; and fish carcasses, which could also be used for biogas or animal feed. As mentioned in Section 5.2.2.3, in the NoM model, all the excess effluent from aquaponics is sent as an export for use in landscaping or agricultural purposes outside of the system boundary. All sludge is then sent to the aerobic digesters to power the aquaponic system. With a standing stock of at least 700 kg of fish, the aquaponic system would be completely self-sufficient with respect to electricity if sludge and crop waste is diverted to anaerobic digesters (Yogev, Barnes et al. 2016), which is achieved in excess in this case study. A portion of the fish are assumed to die of natural causes prior to consumption. These carcasses, as well as the bones of edible fish, are considered an unrecoverable waste in the current model, and thus sent to dissipation; however, in future models, they could be used as inputs for either aerobic digesters or ground down as a soil amendment. Conversely, the abundant effluent that is not absorbed by the plants in the aquaponic systems is considered a recoverable waste product, and thus is exported from the system.

The Black Soldier Fly (BSF) residue produced in zones with higher population densities exceeds the fertilizer requirement in many of these zones, with the current model as constructed. This is because, while excess residue is considered a recoverable waste, it is exported from the system for use outside of the defined system boundary rather than redistributed to neighboring zones or counties. Figure 63 shows the magnitudes of these wastes produced in the NoM case study that need to be explored in further studies to maximize the potential of NoM to retain and cycle nitrogen in the urban boundary.

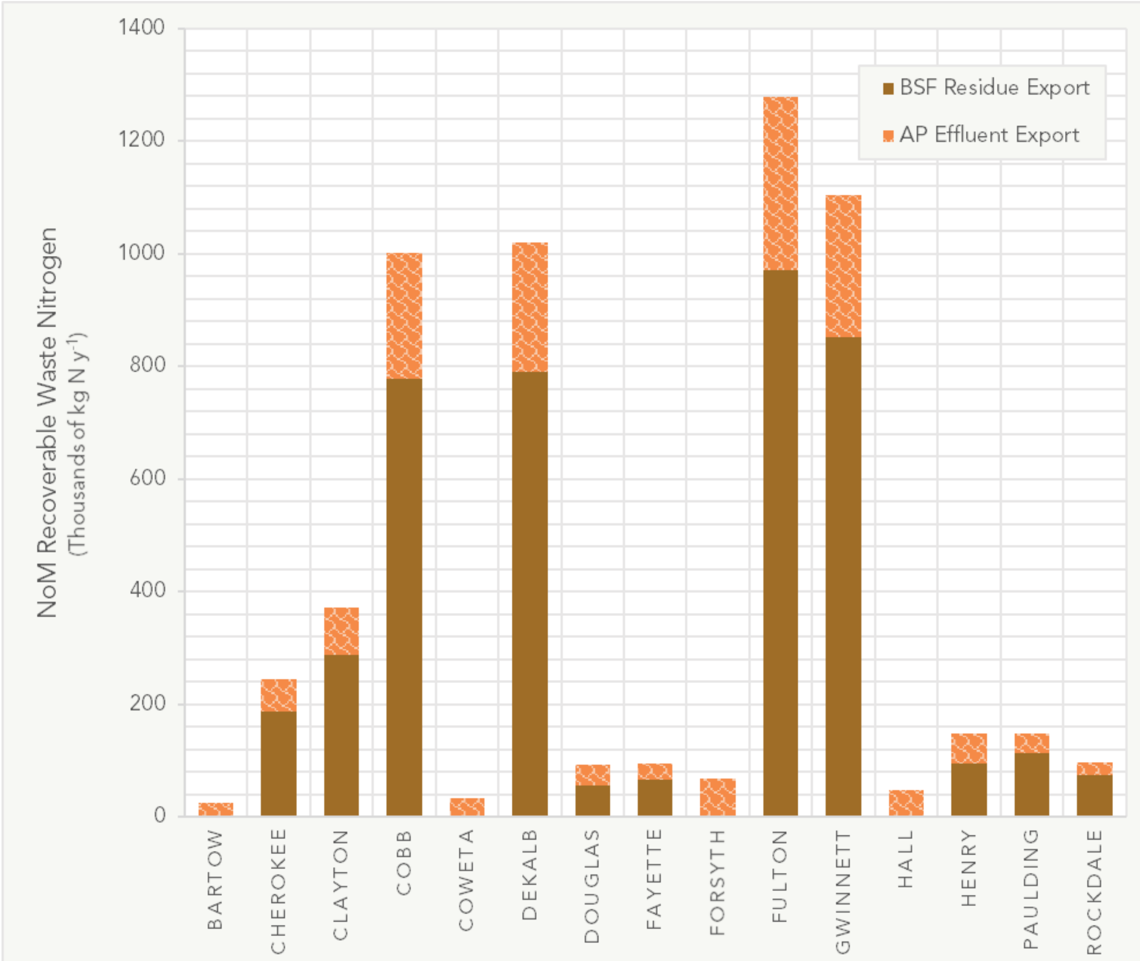


Figure 63: Recoverable waste nitrogen for future optimization, including black soldier fly (BSF) residue and aquaponic (AP) effluent.

As can be seen, the majority of recoverable waste produced in the NoM case study is in the form of BSF residue. Much greater quantities of waste are produced by NoM modules in counties with higher population densities. However, it is in these counties that most of the conventional agriculture takes place. This will be addressed in more detail in Section 5.3.4.

In addition to the new waste, which introduce the need for modified management strategies, land use is also an issue in the NoM model. Using the nitrogen effluent from the wastewater treatment facilities as the input nutrient to fertilize duckweed growth, constructed wetland yield was calculated for each zone. County totals are listed in Table 23.

Table 23: Constructed wetland productivity and nitrogen county totals per year.

County	Duckweed Area Requirement (m2)	Duckweed - horizontal flow area requirement (acres)	Vertical farm area equivalent Duckweed culture (acres)	Duckweed yield (kg DM/year)	Duckweed CP (kg/year)	Duckweed nitrogen (kg/year)
Bartow	142206.78	35.14	2.51	744324.51	260513.58	41682.17
Cherokee	393717.24	97.29	6.95	2060755.38	721264.38	115402.30
Clayton	803294.18	198.50	14.18	4204522.09	1471582.73	235453.24
Cobb	2147222.66	530.59	37.90	11238778.15	3933572.35	629371.58
Coweta	221891.70	54.83	3.92	1161403.36	406491.17	65038.59
DeKalb	2265963.58	559.93	40.00	11860279.97	4151097.99	664175.68
Douglas	304145.78	75.16	5.37	1591929.44	557175.30	89148.05
Fayette	200296.43	49.49	3.54	1048371.53	366930.04	58708.81
Forsyth	455896.48	112.65	8.05	2386207.77	835172.72	133627.64
Fulton	3023487.65	747.12	53.37	15825236.70	5538832.84	886213.26
Gwinnett	2311605.47	571.21	40.80	12099174.17	4234710.96	677553.75
Hall	348169.67	86.03	6.15	1822354.87	637824.21	102051.87
Henry	366073.87	90.46	6.46	1916067.24	670623.53	107299.77
Paulding	183931.69	45.45	3.25	962716.87	336950.90	53912.14
Rockdale	164861.41	40.74	2.91	862901.12	302015.39	48322.46
Total:	**13332764.60**	**3294.59**	**235.33**	**69785023.17**	**24424758.11**	**3907961.30**

As outlined in Section 5.2.2.2, the total area requirement for a vertical flow constructed wetland is found, along with a vertical farm area equivalent, which assumes construction of a 14-story vertical farm to reduce the land requirement by a factor of 14. As can be seen, the area requirement for constructed wetlands that use all the nitrogen effluent from wastewater treatment would be vast. This will be explored further in Section 5.3.4.

5.3.3 NoM vs. Nature and Urban Agriculture Contextualization

In this section, the NoM case study is compared to natural food web metric values and contextualized within the broader Urban Agri-Network discussion. The case studies from the first experiment and the NoM case study are discussed with respect to ecosystem stability, network centralization, the balance between efficiency and redundancy, and the window of vitality. Finally, the NoM flows are evaluated with respect to environmental sustainability using the LCA methods introduced in 4.2.5 and compared to the baseline case study and to the urban farm scenario (see Section 4.3) to evaluate the impacts of nutrient cycling biotechnologies on urban agriculture. These comparisons use the networks in which basins have been removed to enable proper correlation with centralization metrics.

The structure metrics compared here include: Number of Actors (n), Number of Links (L), Linkage Density (L_D), Prey-Predator Ratio (P_R), Fraction Specialized Predator (P_S), Generalization (G), Vulnerability (V), And Cyclicity (λ_{max}). The dimensional metrics (n and L) can be found in Figure 64, and the non-dimensional metrics (LD, PR, PS, V, and G) are found in Figure 64.

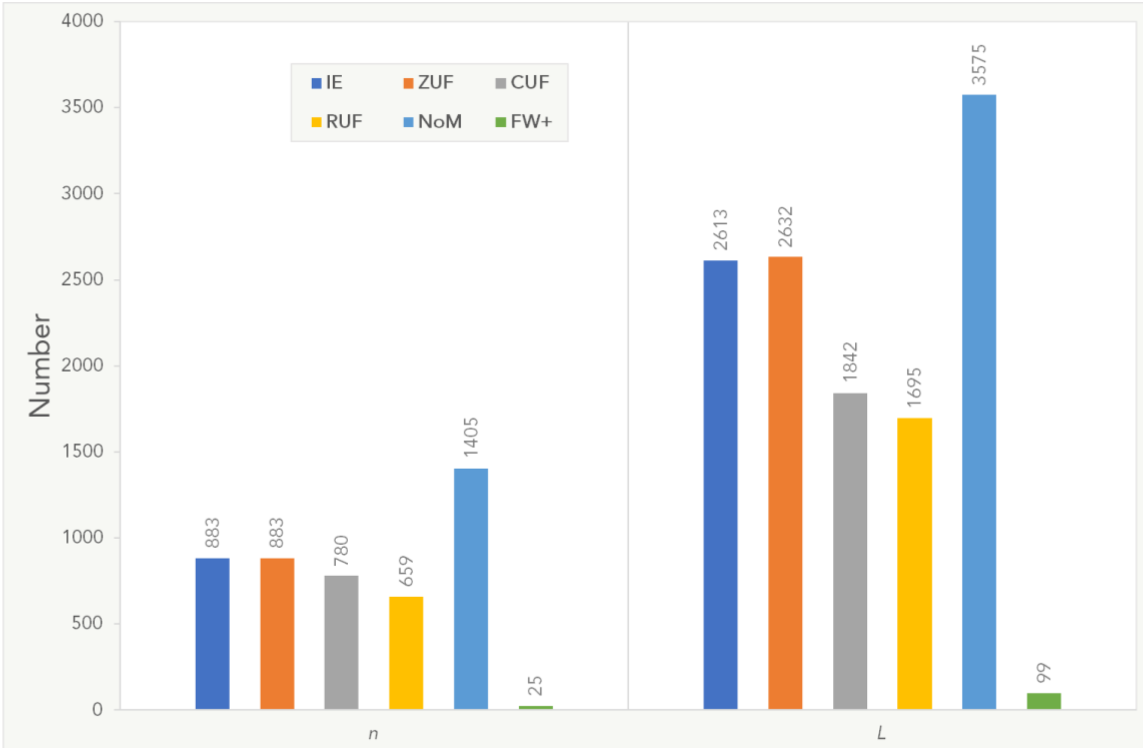


Figure 64:Nutrient Optimizing Module (NoM) case study dimensional structure metrics compared to post-1993 food web median values (Borrett Stuart and Lau Matthew 2014, Layton 2014).

As described previously in Chapter 3, some of the structure metrics are dimensional metrics (n, L, n_{prey}, $n_{predator}$, $n_{s\text{-}predator}$), and these describe numbers of actors or links in the system. There are over 56 times as many actors and over 36 times as many links in the NoM case study as in the natural food webs used in this study. This disparity, and the fact that actors in the NoM case study increase proportionally far more than the number of links, results in further decreased NoM connectance as compared to the previous case studies from the first experiment, and even greater deficit with respect to the natural ecosystem precedent. This is shown in Figure 65.

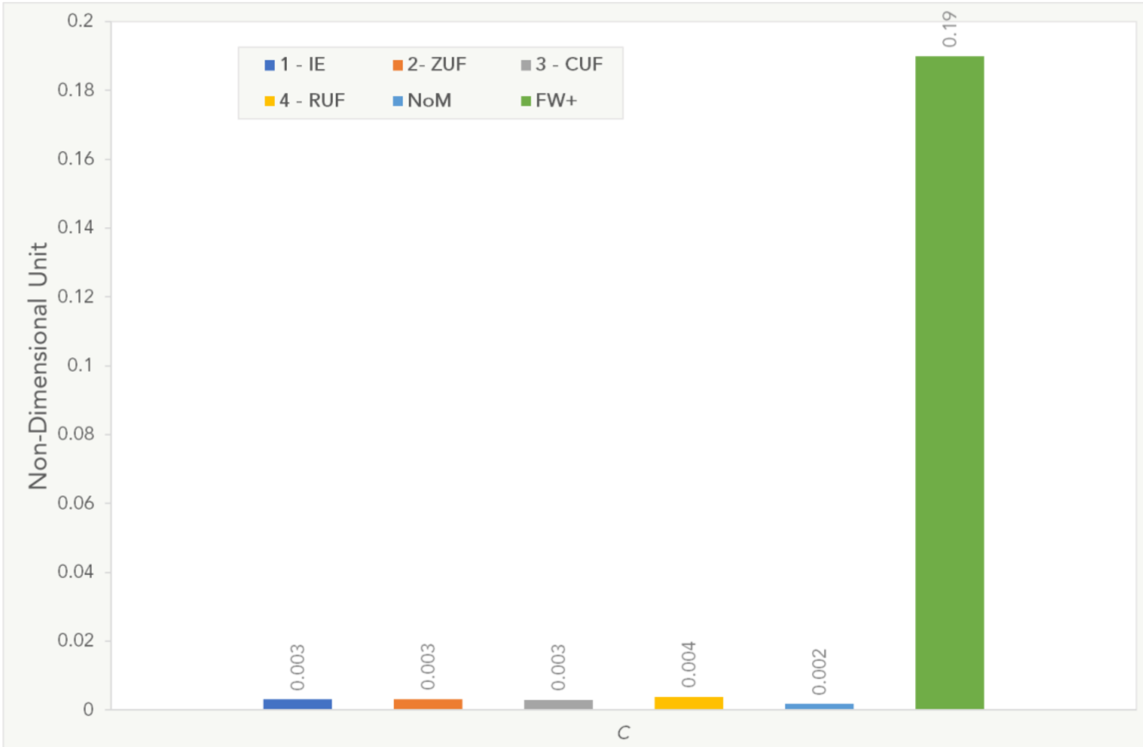


Figure 65: Connectance (C) comparison between all 5 case studies alongside natural food web median C value (with detritus actors) (Borrett Stuart and Lau Matthew 2014, Layton 2014)

The Connectance (*C*) value for the NoM network is the worst of all the case studies. This is likely an underestimate of the actual connectivity that would arise in an urban agriculture system, and could be attributed to the granular detail with which actors are incorporated in this model.

Additional non-dimensional structure metrics are also compared between the 5 case studies and the natural food web median values in Figure 66. These metrics include Linkage Density (L_D), Prey-Predator Ratio (P_R), Fraction of Specialized Predators (P_S), Vulnerability (*V*), Generalization (*G*), and Cyclicity (λ_{max}).

Figure 66: Non-dimensional structure metrics for all 5 case studies alongside natural food web medians (with detritus actors) (Borrett Stuart and Lau Matthew 2014, Layton 2014)

From the structural standpoint, the NoM case study shows improvement over the Agri-Network Centralization Experiment (ACE) case studies (Zone Urban Farm – ZUF, County Urban Farm – CUF, Region Urban Farm – RUF, and Import/Export – IE) in several areas. These include the Cyclicity value, which indicates that the NoM's biotechnology modules do increase cycling from the baseline. However, this value is still 50% lower than the natural food web median value. The faction of specialized predators is also decreased from the ACE cases, showing between 17% and 27% decrease. However, there is still a ways to go before the NoM network achieves the natural food web median, which is only 16% of the NoM value. This means that the "predators" in the NoM network are more specialized, and thus more prone to challenges in the face of food scarcity or removal of their particular food source.

This reduced specialization seems to be true across all 5 case studies, as the Generalization (*G*) and Vulnerability (*V*) values are still significantly lower in all NoM and ACE case studies compared to the natural food web medians, and which means that there are fewer prey for every predator and fewer predators for every prey. In the NoM case, especially, the *G* and day *V* values are reduced by 6% over the lowest ACE vale (IE), which is still 44% lower than the food web median. This means that in general, the actors in the NoM network are more specialized, not less, than those in the ACE case study. In the event of a food shortage in a given zone, these highly specialized actors in the NoM network would likely have trouble finding new food sources (as constructed).

The non-dimensional flow-based ENA metrics are also compared across the 5 networks with respect to the food web median values from after 1993 (Borrett Stuart and Lau Matthew 2014, Layton 2014)Nine ecological flow metrics are calculated for the NoM case study include : Finn's Cycling Index (*FCI*), Mean Path Length (*MPL*), Average Mutual Information (*AMI*), Ascendency (*ASC*), Development Capacity (*DC*), Total System Overhead (*TSO*), Total System Throughflow (*TST*), *ASC/DC*, and Robustness (*R*). The non-dimensional metrics (*FCI, MPL*, *AMI*, *ASC/DC*, and *R*) can be found in Figure 67

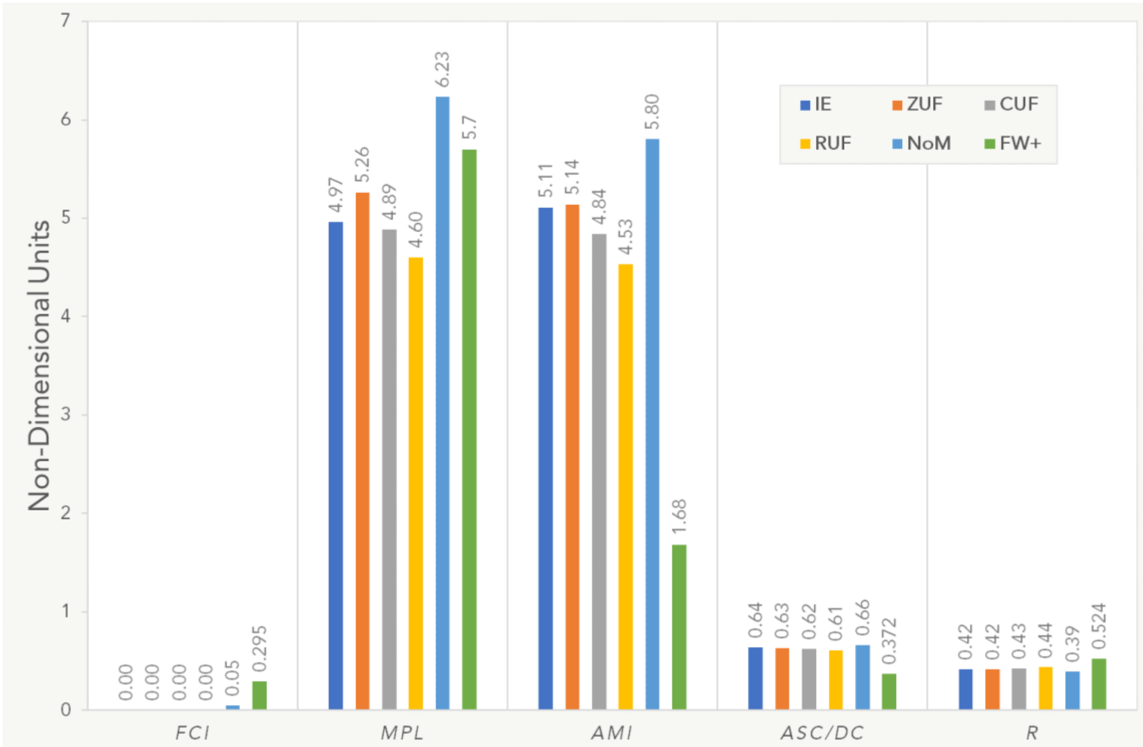


Figure 67: Non-dimensional flow metrics for Nutrient Optimizing Module (NoM) case study (case 5) compared to 4 Agri-Network Experiment (ACE) case studies and the post-1993 food web median values (Layton 2014).

When comparing the NoM case study against food web median flow-metric values, one can see that even with the introduction of cycling actors into the system, the network as constructed deviates in a few key areas from natural food webs. First, Finn's Cycling Index (*FCI*), which accounts for the percentage of material flow that is a product of cycling activity. From the values seen above it can be seen that the NoM network is still severely deficient, with a deficit of 82% of the food web median. However, like the ACE case studies, the NoM case study likely underestimates the amount of cycling activity present in the network, as existing composting pathways are neglected.

Next, there is an increase (9%) in the Mean Path Length (*MPL*) from the food web median value, and an increase of over the next highest *MPL* value (20%, Zone Urban Farm

– ZUF). This means that in the NoM case, material passes through more actors before exiting the system than in any of the other cases evaluated (Finn 1977, Anderson, Rosemarin et al. 2016). This means that the NoM network is relatively complex and that the actors participate to a larger extent in conveying material through the system. This is likely due in part to the positioning of zonal biotechnology modules, who each add additional mediating steps onto the waste pathways that were originally conveyed directly out of the system in the Agri-Network Centralization (ACE) case studies, and in part to the increased cycling afforded by these modules.

Although the actors participate to a larger extent, this has a downside, in that the actors in the NoM construction seem to further constrain the flow paths, tightly controlling the material flows within the system, which is evidenced by the increase to Average Mutual Information (*AMI*). This *AMI* metric, explored in Section 4.4 with respect to the increase seen in the decentralized urban farm scenario (LEF – case 2, which shows a 203% increase over the food web *AMI* median value). Here it can be seen that the NoM case further increases the amount of specialization over the ZUF case (13%), showing an even higher increase over the food web median *AMI* value (243%).

This drastic increase in *AMI* manifests itself in the following two flow metrics, Robustness (*R*) and Ascendancy over Development Capacity (*ASC/DC*), as the level of specialization is weighted by this *AMI* value (Ulanowicz 2000). The NoM imposes additional constraints through further decentralization of the urban food network that result from the addition of NoM actors at the zone level. In the zones, although some additional actors and pathways are added along which food can travel (as evidenced by the increase to *MPL* in the NoM case), the network is constructed in such a way as to severely constrict the flow of material between a strict set of actors in strict sequence. This can be related to NoM's reduced Generalization, Vulnerability, and Prey-to-Predator ratios shown in Figure 66, which highlight the highly specialized structure of the case study. Here, when flows are evaluated, the NoM shows a drastically higher *MPL* (20% over the Zone Urban Farm case, up to a 40% increase over the Region Urban Farm case).

Although there are additional different paths by which materials can flow, this is only true at the zone level, so the relative values of these flows with respect to the total system flows is very small, and the overall system. Additionally, the increased mediation actors handle material from a very limited number of actors and deliver their flows to a similarly limited number of actors, given the specialization of the system. While other studies suggest that increased *MPL* is a desirable design goal for industrial ecosystems(Reap 2009, Layton 2014), in this case the increased MPL this seems to increase the amount of constraint on flows.

5.3.3.1 The Window of Vitality with NoM and ACE Case Studies

In Figure 68, the Window of Vitality curve is presented once more, this time with the Nutrient Optimizing Module (NoM) case study added.

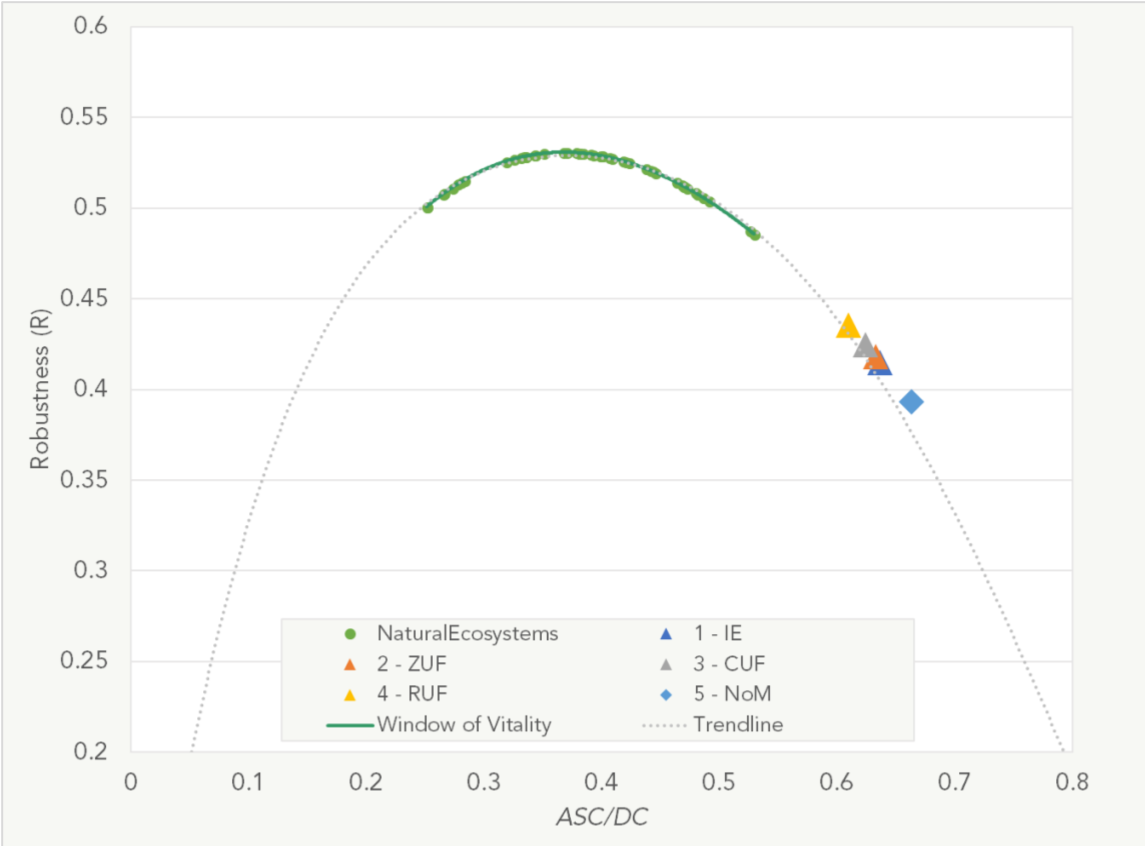


Figure 68: Robustness (R) plotted against Ascendancy (ASC) over Development Capacity (DC) and the "window of vitality" curve for all 5 case studies and select natural ecosystems (Ulanowicz 2009, Layton, Bras et al. 2015).

This representation reiterates the discussion presented in Section 4.4.2. The further decentralized NoM case study appears even more efficient than the ACE case studies, while it also displays a further reduction in the robustness of the system.

Additionally, the trend seen in increasing internal flow magnitude with further decentralization (see Section 4.4.2) is also reinforced in the NoM case. This is illustrated in Figure 69.

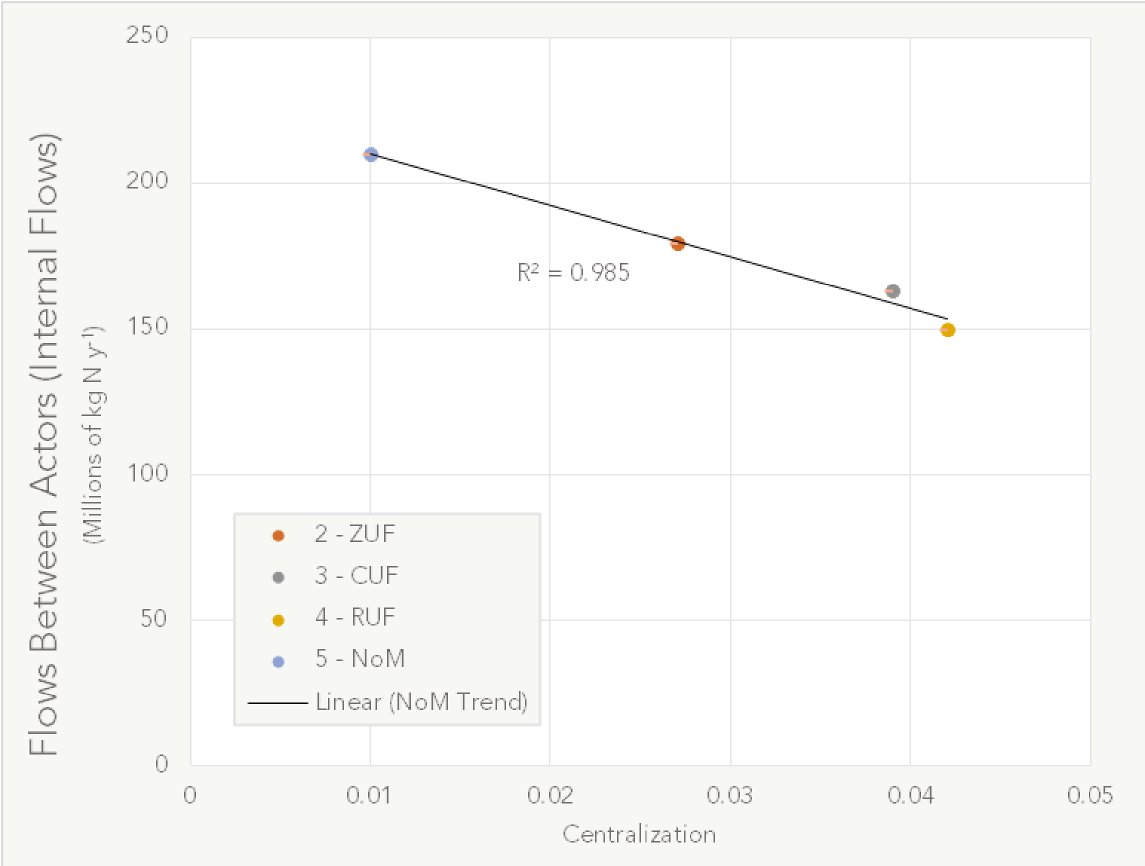


Figure 69: Internal flow magnitudes compared against network centralization.

Once again, as the network is further decentralized with the addition of zone-level NoM actors, the flows are mediated by additional actors. This was demonstrated by the increased mean path length (see Figure 67), but also in the increased internal flow magnitude illustrated in Figure 69 above.

5.3.4 NoM Model Limitations and Future Considerations

5.3.4.1 Supply, Demand, and Land Use

Because of the way in which the model was constructed, excess products produced in zones by NoM modules are exported rather than redistributed in the manner food products were redistributed in the Agri-Network Centralization Experiment. As a result, the potential to offset chemical fertilizer is not fully captured by the results.

Figure 70 shows the deficit and surplus soil nutrient supplied by the Black Soldier Fly (BSF) larvae residues in each county. The figure illustrates that, if the model were reconstructed to redistribute zone products from the nutrient modules, all the fertilizer demand for the Atlanta region could be met by the products of BSF, and there would be excess residue for export from the region.

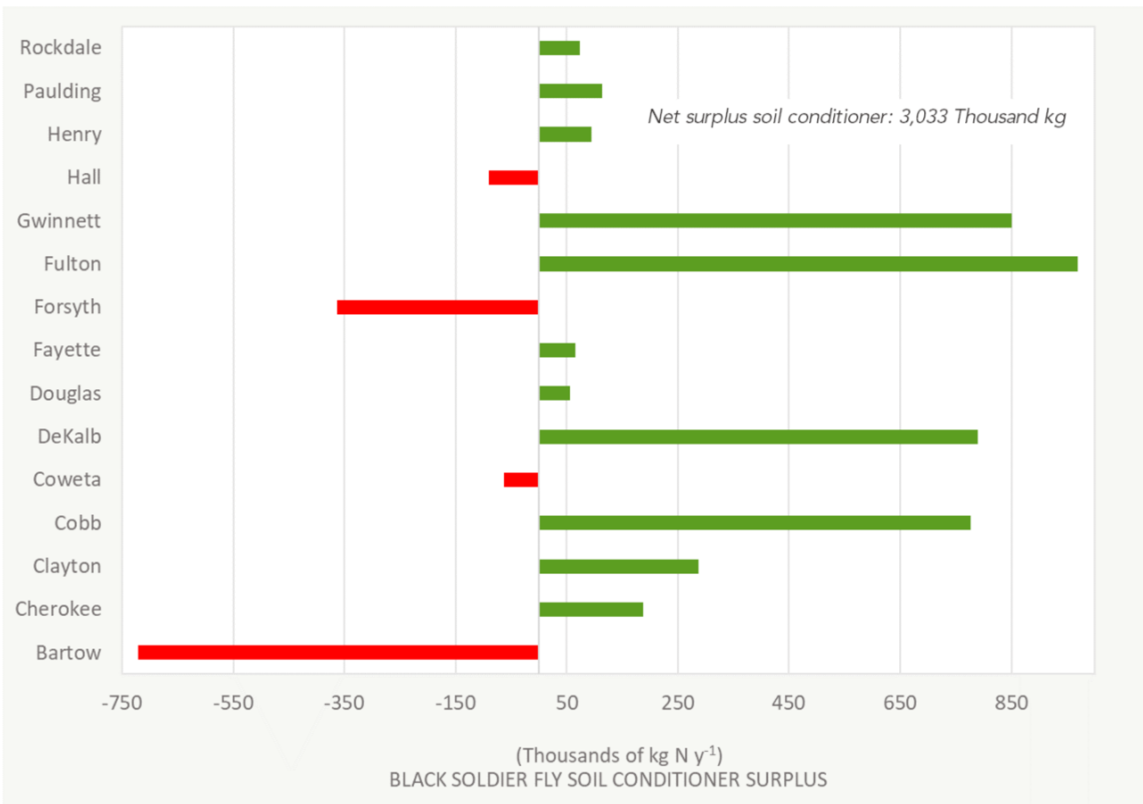


Figure 70: Surplus black soldier fly residue compared to fertilizer requirement in Atlanta Metropolitan Region counties.

The figure also demonstrates that redistribution would be necessary to fully leverage the nutrient module cycling. Here, the mismatch between farming locations and population density leads to a mismatch in the availability of products when zones are treated in isolation. However, in the NoM case study, as opposed to the ACE case studies, more densely populated areas produce much greater quantities of output, as the NoM modules are fed by population waste products. Because flows are constrained in this model, the full benefit of the nutrient cycling biotechnology actors are not fully realized.

Future work should leverage the framework presented in the Agri-Network Centralization Experiment to refine the Nutrient Optimizing Module experiment to include redistribution of nutrient module products. In so doing, the nutrient grid could completely offset the fertilizer imports, as reported by the USDA Census of Agriculture.

Using the availability of nitrogen effluent from the wastewater treatment facilities as the input for nutrient, constructed wetland yield was calculated for each zone. As outlined in Section 5.2.2.2, the total area requirement for a vertical flow constructed wetland was found, along with a vertical farm area equivalent, which would require construction of a 14-story vertical farm to reduce the land requirement by a factor of 14. As can be seen, the area requirement for constructed wetlands that use all the nitrogen effluent from wastewater treatment would be vast. However, when comparing these area totals with the pasture land totals, reported by the USDA Census of Agriculture as usable for farming without upgrade, the results are interesting (Table 24).

Table 24: Constructed wetland area requirement (in acres), with and without vertical farming, compared against pastureland in each county requiring no upgrade for conversion to use as cropland (USDA 2014).

County	Arable pastureland (requiring no upgrade)	CW Land Required		Land Remaining
		Flat Constructed Wetland	Vertical Farm Constructed Wetland	
Bartow	3,767	35	3	3,731.86
Cherokee	450	97.29	6.95	352.71
Clayton	0	198.5	14.18	0
Cobb	362	530.59	37.9	0
Coweta	1,041	55	4	986.17
DeKalb	0	559.93	40	0
Douglas	89	75.16	5.37	13.84
Fayette	296	49.49	3.54	246.51
Forsyth	37	112.65	8.05	0
Fulton	64	747.12	53.37	0
Gwinnett	102	571.21	40.8	0
Hall	434	86.03	6.15	347.97
Henry	450	90.46	6.46	359.54
Paulding	351	45.45	3.25	305.55
Rockdale	90	40.74	2.91	49.26
Total:	**7,533**	**3,295**	**235**	**6,393.41**

As can be seen, there is a mismatch in the available land for farming and the required land for use in a constructed wetland, if all effluent is treated by constructed wetlands without use of vertical farming. (The same is only true in Clayton and DeKalb counties if vertical farming is used for constructed wetlands.) However, if constructed wetlands were constructed wherever land is available, which would require diversion of effluent from its originating zone to zones in neighboring counties, then all the required land requirement could be met using vertical constructed wetlands without vertical farming. This redistribution calculation can be found in Appendix B.

5.3.4.2 Uncertainty, Actors and Data Resolution

When constructing biological, urban, and industrial networks, scientists encounter many layers of uncertainty within their data. This is especially true for large, complex systems of interacting components. Thus, it becomes important to recognize different areas of uncertainty within model assumptions to make the model more transparent to readers and future researchers building upon these models. Historically, scientists have had a great deal of difficulty reconstructing ecosystems or urban systems to model and predict future trends using ecological network analysis (Bodini, Bondavalli et al. 2012, Lau, Borrett et al. 2017). Likewise, urban ecologists and sustainability analysts have encountered similar data deficiencies making use of sparse, if even existent data on the flows and usage of materials and energy (Corominas, Foley et al. 2013). In these models, many assumptions were made, both for the topology and flows within the Atlanta Metropolitan Region discussed in Section 4.4.3, and with respect to NoM component nitrogen efficiency and growth.

In addition to the uncertainties and data scarcity, comparison between the presented networks and the natural food web ENA medians displayed here adds further complication. As can be seen in the size of the networks presented in this thesis ($655 \leq n \leq 1405$), this study attempts to preclude potential loss of resolution by including a strong degree of granularity for food system linkages. This was also done in order to leverage ENA procedures to test the impact of food system decentralization, which would not have been possible if food production actors were lumped into industry-level trophic actors. The degree of species richness in the 5 case studies presented is between 2520% and 5500%

larger than the median value for the food webs sampled in the literature (*n*=25). This difference is likely due to both data resolution and availability for the ecological food webs and to the aggregation so common in ecological practice. In comparing the presented case studies to these natural systems, it is important to keep in mind that some of the resulting ENA metric results can likely be attributed to this discontinuity. Future studies should attempt to aggregate urban food networks in such a way as to mitigate potential incongruencies.

Finally, the metric values presented here further call to mind the question of whether the case studies in these experiments are too minutely divided with respect to actor designation. In other words, are the actors defined in these case studies too finely designated in order to be meaningful, or should they have been aggregated in larger zones? If the biotechnology actors in the NoM case were incorporated as a "Nutrient Optimizing Module" actor at the zone level, this actor would have a large variety of inputs and connections to other actors within the system, thus decreasing the number of actors significantly while retaining a large portion of the links. Given that connectance decreases with the square of the number of actors, this could have far reaching impacts to this particular indicator but also to some of the flow indices presented below. However, it also harkens back to the discussion presented in Section 4.4.2 that more rigorous efforts must be made to determine the appropriate level of aggregation for urban agriculture networks and ecologically-inspired network design at large (Ulanowicz and Kemp 1979, Ulanowicz 2000, Allesina, Bondavalli et al. 2005, Chen, Fath et al. 2010).

5.4 Summary of Nutrient Optimizing Module (NoM) Experiment

This follow-up experiment is designed to test the effects of increased cycling in the most decentralized case study on systems performance from an ecological network perspective. The NoM experiment answered the following question:

- How do ecological network performance, agri-network centralization and embedded life cycle impacts change when biological actors are introduced as recycling modules?

The results of this experiment build on the results of the Agri-Network Centralization Experiment, finding that increased urban self-sufficiency and reduced environmental burden can be achieved when food is produced within the urban boundary. This is demonstrated by the increased cycling afforded by the biotechnologies, and the NoM case study enables a 15% increase in food production as compared to the urban farm case presented in Chapter 4, resulting in further reduction of impacts due to food miles. The NoM network has an increased Average Mutual Information, indicating that it has increased in its stage of development over the urban farm scenario case studies. However, the NoM network is further decentralized than the case studies presented in the first experiment, and confinement of flows into localized food sub-networks confines flow paths and reduces overall robustness. The results suggest that the actors in the further decentralized NoM network is overly specialized, in that flows between NoM actors are far too limited in their interactions and connectance. The confined flow paths that do not allow for restructuring in the event of a perturbation.

A more realistic model should be constructed in which zone populations have a diverse set of groceries and restaurants from which they can purchase foods, and where zonal farms have the ability to distribute to a variety of groceries and potentially directly to restaurants and populations. This will likely result in more favorable network metrics such as redundancy and flow path flexibility that could shift and adjust when faced with disturbed food supply. Future iterations of the NoM model should also test the impacts of a more centralized urban agri-network, which was demonstrated previously in Chapter 4 to come closer to achieving a healthy balance between redundancy and efficiency. With the added cycling afforded by the NoM modules and a redistribution network that facilitates supply-demand optimization, future iterations of the NoM network will likely come much closer to the ecosystem benchmarks.

CHAPTER 6. THE NUTRIENT MICROGRID: SYNTHESIS AND CONCLUSIONS

The methods presented in this thesis provide a framework to evaluate possible configurations and functional improvements to food flow networks in this unique urban center. Chapter 2 provided a backdrop onto which the application of ecosystem-inspired design and systems evaluation was presented and then highlighted some recent urban and industrial material flow and food system studies to provide context for several food system designs. Using ENA and additional network indices and evaluated to gage the relative environmental impact of imports to the systems,

Results from these analyses suggest that restricting food procurement into localized areas increases the efficiency of the network, but this is at a cost to overall system redundancy. If any link in this network were to be severed, his could result in a fragmented food system, where some areas produce more than they can consume while others require more than they can produce. This becomes especially apparent when nutrient cycling modules are introduced at the most localized level in the Nutrient Optimizing Module experiment, where areas with dense populations can exceed their soil amendment needs but lack space to accommodate constructed wetlands to treat their waste. By contrast, this very fragmentation of the NoM network may serve to shield subsystems from disturbances elsewhere in the system, providing a buffer from threats such as disease or crop pathogens that may otherwise threaten food supplies locally. This demonstrates the need for a combined approach to nutrient management that applies both the flow-path flexibility of a centralized system, exhibited by the Region Urban Farm Case, and the efficiency and cycling afforded by a localized system characteristic of the Nutrient Optimizing Module. In this chapter, nutrient microgrid components and considerations are presented along with additional technologies and analysis that should be explored in future research.

6.1 Ecosystem Development, Maturity, and Stability

In the urban food system context, the underlying functional requirements are: 1) adequate provision of food; and 2) sanitary disposal of waste. However, in a sustainable urban environment, businesses and infrastructure must also be maintained while the natural environment is nurtured, in order that the economic and ecological services provided by these may continue to flourish for future generations (Brundtland 1987). In the case of food production systems, perhaps the most recognized potential disturbance would be caused by climate change, whereby water shortages and hindered ecological activity could threaten the food supply. In this instance, highly-connected, redundant sources of food from a diverse set of production source paths might help to mitigate disturbance to a given city's food supply.

By contrast, pathogens such as salmonella and E. coli present a different kind of disturbance, one that would require containment rather than redundancy or dispersal. In the face of such a disturbance, food supply chains may more effectively be stabilized by isolation of the pathogen via more isolated food hubs or modules. This kind of confinement or compartmentalization manifests itself as "modularity" in ecology (Newman 2006).

The more decentralized urban agriculture networks (Zone Urban Farm and Nutrient Optimizing Module cases) appear to be the worst of the networks constructed in this study in their balance between redundancy and efficiency. This is because flow of material is much more constrained in the ZUF and NoM models, with far more efficient movement of materials between zone-level actors with decrease dependency on the central actors at the county and regional level. However, NoM has increased self-sufficiency with respect to inputs and reduced waste, or connections to dissipation, in addition to reduced indirect connections to neighboring zones. In the presence of a plant or livestock pathogen outbreak, the NoM configuration may be partially protected from the pathogen due to its reduced connectivity to outside producers and suppliers.

A more realistic network construction would enable flexibility for food procurement pathways, enabling food flows to population actors to come from a variety of grocery locations. ENA has been traditionally used as descriptive rather than prescriptive. As a result, there is currently no standardized mechanism by which food system designers could build in flexibility into flow paths to add diversity or elasticity into food flows to consumers in a network. This will be required to adequately describe a realistic food system. If these flexible pathways were built into the system, the results would be quite different for the redundancy or robustness metric, and the resulting network would most likely improve in its situation in the window of vitality curve of each of these decentralized cases.

6.2 Future Model Considerations

6.2.1 Model Refinement and Improvements to Case Studies

Land use and available space in the Atlanta Metropolitan Region has not been thoroughly explored in the present study. According to the 2012 Census of Agriculture, the USDA estimates there are an additional 7,533 acres of pasture land in the system boundary that are available for transformation to cropland (USDA 2014). This land availability should be explored in more depth, along with additional rooftop or warehouse space existing in the region, to evaluate the feasibility and economic viability of conversion or construction of vertical farms in the region. Future work should incorporate geospatial data, employing similar strategies used by (Clinton, Stuhlmacher et al. 2018), to catalogue and evaluates with higher resolution potential for urban farming in the Atlanta Region.

Legumes were excluded from this study because of their vastly different nitrogen requirements and use, because of their symbiotic relationship with nitrogen-fixing bacteria. For this reason, in addition to the natural volatilization of nitrogen at every step of the process, the nutrient microgrid proposed here cannot be fully nitrogen self-sufficient. However, with the inclusion of legumes, it is possible that the nutrient microgrid could become more self-sufficient with respect to nitrogen flows. This should be evaluated in future iterations of the Nutrient Optimizing Module.

Additionally, existing composting of manure and food waste is not considered in this model. This area of research is largely untapped to date, and the Atlanta Metropolitan Region has sparse or even negligible pathways for information gathering and dissemination regarding composting. This is an area that needs to be explored in much greater depth to augment the presented nutrient grid to build a more robust picture.

Finally, the inclusion of a linkage between the produce and poultry actors in the Atlanta Metropolitan Region is overlooked in the present analysis due to the lack of data available. This important and likely substantial linkage needs further explored and assumptions should be made regarding the percentage of locally cultivated feed is present in the baseline system. Future models should not only include a linkage, but they should include varying degrees of connectivity and localization to fully build out an accurate picture of the current and potential food network.

6.2.1.1 Pyrolysis and Biochar

One shortcoming of the present Network Centralization and NoM models is the losses of N to ammonia volatilization. One could mitigate the losses that occur of ammonia to dissipation by incorporating biochar into water conveyance and grow structures in both wetlands and aquaponic operations. Biochar has been shown to reduce ammonia losses in both agricultural applications and in aquaponic setups (Bleuler and Schönborn 2017) and it has been demonstrated to improve crop yield when used as a growth substrate in hydroponics (Awad, Lee et al. 2017).

Additionally, pyrolysis could be implemented as a means of treating crop stover rather than or in addition to using it as a BSF feed. This would provide increased network stability by providing diversity of end uses for these materials, which might otherwise build up due to mismatched loads and requirements. Moreover, crop stover is available only periodically, and thus will be in abundance at certain times of year, leading to fluctuation in feedstock for BSF. Providing additional pathways for usage would help to buffer supply and demand mismatches or fluctuations.

6.2.1.2 Source Separation

Separation of waste streams at the site of generation has been cited as the most effective way to optimize nutrient retention and minimize losses (Simha and Ganesapillai

2017). The data compiled for this study has been done with the intention of incorporating future analysis using source separation to mediate interactions between humans and their environment. Separating food waste and waste water constituents at the point of production of such wastes provides additional opportunities for HTW iteration. As such, this study separates food waste into MSW and that of wastewater via kitchen sink waste processor. While this distinction is not expressly explored in this thesis, the relegation will be important to future work, when source-separation should be considered.

Source separation may also be facilitated by shifting patterns of food procurement by the population. For example, meal kit delivery services offer customers pre-prepped vegetables and food products. Distributors handle high volumes of food waste and inedible organic matter, essentially aggregating waste without the need to recollect it. As the Region Urban Farm and County Urban Farm models demonstrate, it is possible that networks are made more robust when producer actors do not have complex and constrained distribution chains for dispersal and collection of food products for later distribution to consumer actors.

The next iteration of the NoM experiment should treat waste by diverting separate streams before they enter WWTP actors. Duckweed has been used to treat raw wastewater, and by incorporating urine diversion toilets into the network, the NoM might more effectively retain N that is otherwise lost during denitrification and sublimation during the wastewater treatment process (Wilsenach and Van Loosdrecht 2006). Data is also collated and ready to be analyzed for different combinations of feedstock for black soldier flies. The present model uses municipal solid waste and human biosolids from both wastewater treatment and septage streams, but alternative feedstock permutations have also been compiled, including wastewater biosolids only, crop waste and food waste only, and a combination of septage and wastewater biosolids, municipal solid waste, and crop waste. The subsequent flows of nitrogen to the aquaponic fish have been likewise collated for each of these scenarios. A comprehensive analysis should be conducted that evaluates the economic feasibility, the social viability, and the environmental impacts of each of these scenarios, incorporating the network approach presented in this study.

6.2.2 Supply-and-Demand Optimization Through Distributed Food Networks

The integration of nutrient-cycling infrastructure suggested in this study will require a massive coordination effort. The implementation of a closed-loop strategy might elicit a mismatch of nutrient availability and demand (Wielemaker, Weijma et al. 2018), requiring coordination, redundancies, and diversification of usage pathways. The different time scales on which consumption and production operate may lead to buildups or deficits in different parts of the system. Sensors, big data, and the Internet of Things provide the perfect complement to the NoM concept, in a similar manner as they do in the smart grid urban planning arena, especially if these are combined with a distributed control structure.

6.2.2.1 <u>Sense-able Agri-Waste-Networks</u>

Nutrient monitoring is historically costly and inconsistent, and farmers have tended to treat cropland using uniform application of fertilizer. Traditionally, farmers need to sample soil and send it to labs for expensive analysis to determine nutrient requirements for crops. However, nitrogen sensors, once prohibitively expensive, have become more affordable and more precise as research continues to progress. This increased availability has led to an increased use of sensors on site in the field (dos Santos 2016, Tzounis, 2017). Precision agriculture, or “smart farming,” a new and growing trend in efficient farming, is enabled through use of these sensors along with geographic planning tools. Wireless sensor networks are increasingly being implemented in the field, enabling farmers to treat cropland in a dynamic and tailored fashion, in contrast to traditional treatment of land with uniform water, nutrient, and amendment applications.

Sensors are also becoming more commonplace in decentralized wastewater treatment systems. Where large, centralized facilities have been designed to manage a wide range of influent with huge variations in characteristics and concentrations, decentralized facilities, characteristic of sanitation strategies proposed in this thesis, are more cite-specific. Increasingly, these systems employ sensors to regulate their treatment of waste depending on influent characteristics (Fuchs 2009). When these waste treatment systems are used in combination with CEA to supply nutrient to food grow systems, data sensor-collected data will help facilitate the coordination of nutrient supply and demand. The data will also help to inform network scaling or the addition or removal of modules as necessary, making long term applications more feasible.

6.2.2.2 Distributed Networks

This study looks at the relative level of urban agri-network decentralization, but future studies should also investigate levels of “distributed” control and flows in the urban context. In nature, many communities operate using decentralized control. One of the most widely cited “distributed” biological system is that of certain insect colonies, where control and task-allocation is distributed among individual actors. In these colonies, complex, global behavior emerges from the sum of local actions and exchanges (Gordon 2010). Without any form of central control, these insects act on local stimuli, perform required tasks, and respond to changing conditions in the colony environment to create a network effect. If their network of communication and control was to be analyzed, these control networks would have lower levels of centralization than a community in which one or few individual actors dictate the actions of the other members. This kind of decentralized, distributed control network topology often relies on transfer of chemical signals from one individual to others in the community (Green and Gordon 2003), and its discovery in nature has spurred the development of genetic algorithms for routing dynamic computer networks (NK and Viswanatha 2009).

Space availability and population are inversely correlated, resulting in increased production in areas that are sparsely populated and increased demand in areas that are densely populated. By contrast, waste, and by extension plant nutrient, is much more available in the highly populated areas. Any urban food production strategy will likely require close coordination with hinterlands or peri-urban areas, where space is abundant, and population is sparse. There is also strong need for space for waste processing in densely populated areas. When aquaponic operations are incorporated, although food supply is largely supplemented by these producer modules, the space requirement calculated for implementing nutrient modules is considerable. These concepts provide further incentive to explore a “distributed” network model, whereby zone nodes are connected in a more flexible, decentralized manner. This may enable zones to connect supplies of nutrient to space for cultivation, and further enhance nutrient cycling capabilities within the urban and peri-urban areas, without the hierarchy presented in this study, which seem to over constrain flow paths.

A sustainable food system will balance efficiency and redundancy by intelligently matching local needs and decentralized production using heuristic optimization strategies borrowed from electricity "smart grid" research (Logenthiran, Srinivasan et al. 2012). Such microgrid optimization strategies, when applied to the nutrient grid, will incorporate demand-side as well as supply-side management (Saad, Han et al. 2012) whereby nitrogen flows will be optimized and redistributed within the greater metropolitan region using sensor-controlled monitoring feedback loops, which will likely be augmented by distributed control strategies.

6.3 Conclusions

Incorporating nutrient cycling into the urban food network will be one of the most important challenges of the 21st century as populations shift from rural to urban areas. The disjointed, segregated design of food production and waste management networks, in their current iterations, has led to the emergence of undesirable effects, such as air and water pollution and dwindling resources. This is a missed opportunity for material cycling that warrants innovative synthesis of agriculture and new sanitation concepts. This study links the peri-urban food production with urban food fluxes to provide a holistic view of the multi-faceted nutrient network, providing future researchers with a framework to augment the system as it has been described and better evaluate the food network in later studies.

Results from this study demonstrate that when food is retained within the system boundary, ecological metric values can be brought slightly closer to those found in natural ecosystems. The Nutrient Optimizing Module Experiment demonstrates that nutrients and organic matter can be reused in agriculture by employing *symbiotechnology* modules that recover resources from sanitation and wastewater management systems. Through the incorporation of these modules into Atlanta's food network, we can alleviate some of the material use and management pressures facing both production and waste systems. However, to adequately quantify impacts to the overall network that changes will incur, further work will be required to more appropriately incorporate flow path flexibility and to quantify tradeoffs to environment, populations, and the economy that changes will induce.

This thesis builds upon ENA with additional network metrics to further inform sustainable food network design and bring the field a bit closer answering questions of scale and decentralization in sustainable agriculture. Analysis suggests that localized food production results in increased network efficiency, and when recycling actors are incorporated, the decentralization increases modularity. However, due to the way the presented networks are constructed, this increased efficiency and modularity seems to be at the cost of robustness, as the network becomes overly constrained and nitrogen flow-paths are restricted. Simulations should be conducted that incorporate flow path flexibility, whereby consumers can select a range of grocery store locations and farmers can sell to neighboring zones. This may reduce the over constraint of flow paths, but it will also likely reduce the average mutual information (Fath, Scharler et al. 2007, Ulanowicz 2009). Additional work should be done to evaluate environmental impacts on the use-phase of nutrient cycling modules, including energy consumption, transportation requirements, and water use. Further, community-level structure and flow analysis should be adapted to investigate the nutrient microgrid to detect the emergence of network behaviors at the subsystem level within the region and evaluate intra-network patterns. More work is needed to arrive at an environmentally-sustainable configuration of Atlanta's regional food network actors, but the ecologically-inspired network approach presented here offers a promising framework in which future nutrient microgrid iterations can be achieved.

APPENDIX A. AGRI-NETWORK CENTRALIZATION EXPERIMENT SUPPORTING DATA AND SELECTED FLOW TABLES

A.1 Wastewater

A.1.1 Supporting Wastewater Treatment Data

Table A1: Wastewater treatment actors, county and zone population data

Wastewater Treatment Plants[3]	Basin	2016 Permitted Capacity (MGD)	Proportion of county total flow (%)[4]	Zone Population (number)[4]	Zone Population Under 20 (number)[4]
Adairsville North WPCP	Coosa	1	5.83	5,840	1,719
Adairsville South WPCP	Coosa	0.5	2.92	2,920	860
Cartersville*	Coosa	15	87.46	87,601	25,788
Bartow Southeast	Coosa	0.1	0.58	584	172
Bartow Two Run Creek	Coosa	0.1	0.58	584	172
Emerson Pond	Coosa	0.45	2.62	2,628	774
	Bartow County Total:	**17.15**	**100.00**	**100,157**[1]	**29,484**[2]
Canton	Coosa	4	22.86	48,993	14,633
CCWSA Fitzgerald Creek	Coosa	5	28.57	61,242	18,291
CCWSA Rose Creek	Coosa	2	11.43	24,497	7,316
CCWSA Rose Creek	Coosa	4	22.86	48,993	14,633
Woodstock	Coosa	2.5	14.29	30,621	9,145
	Cherokee County Total:	**17.5**	**100**	**214,346**[1]	**64,018**[2]
Clayton WBCasey/Huie WRF*	Ocmulgee	6.6	19.19	49,773	15,920
Clayton WBCasey/Huie WRF*	Ocmulgee	17.4	50.58	131,220	41,971
Clayton Northeast WRF	Ocmulgee	6	17.44	45,248	14,473
Clayton Shoal Creek WRF (panhandle Wetlands)	Flint	4.4	12.79	33,182	10,613
	Clayton County Total:	**34.4**	**100**	**259,424**[1]	**82,018**[2]
Cobb Noonday Creek WRF	Coosa	20	17.86	122,871	34,715
Cobb Northwest WRF	Coosa	12	10.71	73,723	20,829
Cobb RL Sutton WRF	Chattahoochee	40	35.71	245,742	69,430
Cobb South WRF*	Chattahoochee	40	35.71	245,742	69,430
	Cobb County Total:	**112**	**100**	**688,078**[1]	**194,404**[2]
Newnan Wahoo Creek WCPC	Chattahoochee	3	44.82	55,984	16,968
Newnan Mineral Springs WCPC	Chattahoochee	0.75	11.21	13,996	4,242
		0.023	0.34	429	130
Coweta Arnall/ Sargent WCPC	Chattahoochee	0.06	0.90	1,120	339
Coweta Arnco WCPC	Chattahoochee	0.1	1.49	1,866	566
Coweta Shenanhdoah WCPC*	Flint	2	29.88	37,323	11,312
Grantville - Colley Street LAS	Chattahoochee	0.15	2.24	2,799	848
Grantville Ponds	Chattahoochee	0.12	1.79	2,239	679
Senoia LAS	Flint	0.49	7.32	9,144	2,771
	Coweta County Total:	**6.693**	**100**	**124,900**[1]	**37,856**[2]

Table A1 (continued)

DeKalb Polebridge WPCP	Ocmulgee	20	35.71	247,105	65,406
DeKalb Snapfinger Creep WCPC	Ocmulgee	36	64.29	444,788	117,731
	DeKalb County Total:	**56**	**100**	**691,893**[1]	**183,137**[2]
DDCWSA South Central WPCP	Chattahoochee	6	48.74	64,534	20,083
DDCWSA Rebel Trails WPCP	Chattahoochee	0.04	0.32	430	134
DDCWSA Northside WPCP	Chattahoochee	0.6	4.87	6,453	2,008
DDCWSA Sweetwater Creek WPCP*	Chattahoochee	3	24.37	32,267	10,041
Villa Rica North WPCP	Chattahoochee	0.52	4.22	5,593	1,741
Villa Rica West WPCP	Tallapoosa	2.15	17.47	23,125	7,196
	Douglas County Total:	**12.31**	**100**	**132,403**[1]	**41,203**[2]
Fayetteville Whitewater Creek WPCP	Flint	5	45.45	48,440	13,986
Peachtree City Rockaway WPCP*	Flint	4	36.36	38,752	11,189
Peachtree City Line Creek WPCP	Flint	2	18.18	19,376	5,594
	Fayette County Total:	**11**	**100**	**106,567**[1]	**30,769**[2]
Cumming Bethelview Road WPCP*	Chattahoochee	8	57.06	146,476	32,344
Cumming Habersham WPCP	Chattahoochee	0.11	0.78	2,014	445
Forsyth Windermere Urban Reuse LAS	Chattahoochee	0.55	3.92	10,070	2,224
Forsyth Fowler Water Reclamation Facility	Chattahoochee	1.75	12.48	32,042	7,075
Forsyth Manor Water Reuse Facility	Coosa	0.5	3.57	9,155	2,021
Forsyth Dick Creek WRF	Chattahoochee	0.76	5.42	13,915	3,073
Forsyth James Creek	Chattahoochee	1	7.13	7,144	2,103
Forsyth Shakerag WRF	Chattahoochee	1.25	8.92	8,930	2,629
Forsyth Parkstone at the Bridges LAS	Coosa	0.1	0.71	1,831	404
	Forsyth County Total:	**14.02**	**100**	**231,577**[1]	**52,317**[2]
Fulton Johns Creek WRF	Chattahoochee	15	5.83	53,710	14,419
Fulton Big Creek WRF*	Chattahoochee	24	9.33	85,935	23,071
Fulton Little Bear Creek WRF	Chattahoochee	0.1	0.04	358	96
Fulton Cauley Creek Water Reclamation Facility	Chattahoochee	5	1.94	17,903	4,806
Fulton Little River WRF	Coosa	1	0.39	3,581	961
Fulton Camp Creek WPCP*	Chattahoochee	24	9.33	85,935	23,071
Atlanta RM Clayton WRC*	Chattahoochee	100	38.90	358,063	96,127
Atlanta Utoy Creek WRC	Chattahoochee	40	15.56	143,225	38,451
Atlanta South River WRC	Chattahoochee	48	18.67	171,870	46,141
	Fulton County Total:	**257.1**	**100**	**920,581**[1]	**247,143**[2]
Gwinnett F. Wayne Hill WRC	Chattahoochee	40	39.90	321,325	101,836
Gwinnett F. Wayne Hill WRC	Chattahoochee	20	19.95	160,663	50,918
Gwinnett Crooked Creek WRF*	Chattahoochee	16	15.96	128,530	40,734
Gwinnett Yellow River WRF	Ocmulgee	22	21.95	176,729	56,010

Table A1 (continued)

Buford Southside WPCP	Chattahoochee	2	2.00	16,066	5,092
Buford Westside WPCP	Chattahoochee	0.25	0.25	2,008	636
	Gwinnett County Total:	**100.25**	**100**	**805,321**[1]	**25,226**[2]
Gainesville Flat Creek WRF*	Chattahoochee	12	63.04	113,276	34,766
Gainesville Linwood WRF	Chattahoochee	5	26.27	47,198	14,486
Flowery Branch WPCP	Chattahoochee	0.4	2.10	3,776	1,159
Flowery Branch WPCP	Chattahoochee	0.51	2.68	4,814	1,478
Spout Springs LAS	Chattahoochee	0.75	3.94	7,080	2,173
Lula Pond WPCP	Chattahoochee	0.375	1.97	3,540	1,086
	Hall County Total:	**19.035**	**100**	**179,684**[1]	**55,148**[2]
Henry Bear Creek LAS	Flint	1.25	7.14	14,566	4,677
Henry Indian Creek LAS	Ocmulgee	1.5	8.57	17,479	5,612
Henry Walnut Creek WRF*	Ocmulgee	8	45.71	93,221	29,930
Locust Grove Indian Creek WPCP	Ocmulgee	1.5	8.57	17,479	5,612
McDonough Walnut Creek WPCP*	Ocmulgee	2	11.43	23,305	7,482
Hampton WPCP*	Flint	1.75	10.00	20,392	6,547
Stockbridge WPCP	Ocmulgee	1.5	8.57	17,479	5,612
	Henry County Total:	**17.5**	**100**	**203,922**[1]	**65,471**[2]
Dallas Pumpkinvine Creek WPCP	Coosa	1.5	23.69	33,710	11,084
Paulding County Coppermine WRF*	Chattahoochee	1	15.79	15,815	4,656
Paulding County Coppermine LAS	Chattahoochee	1.033	16.31	23,215	7,633
Paulding Pumpkinvine WRF	Chattahoochee	1.5	23.69	23,723	6,983
Paulding Pumpkinvine LAS	Coosa/Etowah	1	15.79	15,815	4,656
Paulding Upper Sweetwater WRF	Chattahoochee	0.3	4.74	6,742	2,217
	Paulding County Total:	**6.333**	**100**	**119,020**[1]	**37,228**[2]
Rockdale Quigg Branch WRF*	Ocmulgee	8	78.28	66,705	19,918
Rockdale Almand Branch WPCP	Ocmulgee	1.25	12.23	10,423	3,112
Rockdale Honey Creek WPCP	Ocmulgee	0.3	2.94	2,501	747
	Rockdale County Total:	**10.22**	**100**	**85,215**[1]	**24,445**[2]
	District Total:	**691.511**	**100**	**3,649,510**[3]	**3,752**[4]

LAS = Land Application Systems
[1](AECOM 2009)
[2] (ASCE of Georgia 2014)
[3] (AECOM 2009)

A.1.2 Calculated Wastewater Flows

Table A2. Fulton County Wastewater Treatment Plant (WWTP) calculated nitrogen flows.

Zone (No.)	Total raw N to WWTP (kg N/year)	WW N to effluent (20.4%) (kg/year)	WWTP N to solids (15.6%) (kg/year)	WWTP effluent N to reuse (18% of effluent) (kg/year)	WWTP effluent N to discharge (78% of effluent)	WWTP solids N to landfill (54%) (kg/year)	WWTP solids N to farmland (20%) (kg/year)	WWTP solids N to incineration (21%) (kg/year)	WWTP solids N to air (all incineration) (kg/year)
58	252342.5	51704.9	39539.1	9306.9	49182.7	21351.1	7907.8	8303.2	8303.2
59	403743.2	82726.9	63261.7	14890.8	78691.4	34161.3	12652.4	13285.0	13285.0
60	1682.0	344.6	263.5	62.0	327.8	142.3	52.7	55.3	55.3
61	84112.6	17234.7	13179.4	3102.2	16393.9	7116.9	2635.9	2767.7	2767.7
62	16824.4	3447.3	2636.2	620.5	3279.2	1423.5	527.2	553.6	553.6
63	403743.2	82726.9	63261.7	14890.8	78691.4	34161.3	12652.4	13285.0	13285.0
64	1682266.0	344695.9	263591.0	62045.3	327881.5	142339.1	52718.2	55354.1	55354.1
65	672905.4	137878.2	105436.3	24818.1	131152.4	56935.6	21087.3	22141.6	22141.6
66	807486.5	165453.8	126523.5	29781.7	157382.9	68322.7	25304.7	26569.9	26569.9
Fulton Total:	4325105.9	886213.3	677692.5	159518.4	842983.3	365953.9	135538.5	142315.4	142315.4

Table A3: Calculated septic nitrogen flow values for Fulton County.

Zone (no.)	Total N to septic system (kg N/year)	Septic N to septage (15%) (kg N/year)	Septic N to effluent (85%) (kg N/year)	Septage N to land (60%) (kg N/year)	Septage N to WWTP (40%) (kg/year)
58	18550.1	2782.5	15767.6	1669.5	1113.0
59	29679.8	4452.0	25227.8	2671.2	1780.8
60	123.6	18.5	105.1	11.1	7.4
61	6183.3	927.5	5255.8	556.5	371.0
62	1236.8	185.5	1051.3	111.3	74.2
63	29679.8	4452.0	25227.8	2671.2	1780.8
64	123666.1	18549.9	105116.2	11129.9	7420.0
65	49466.4	7420.0	42046.4	4452.0	2968.0
66	59359.6	8903.9	50455.7	5342.4	3561.6
Fulton Total:	317945.5	47691.8	270253.7	28615.1	19076.7

A.2 Population

A.2.1 Supporting Consumption and Waste Data

The following tables provide supporting documentation used to calculate wastewater and food flows to and from the urban population.

Table A4: Characterization of feces and urine (Rose, Parker et al. 2015).

		Unit	Mean
High income	Wet weight	g cap^{-1} day^{-1}	149
	Dry weight	g cap^{-1} day^{-1}	30
Low income	Wet weight	g cap^{-1} day^{-1}	243
	Dry weight	g cap^{-1} day^{-1}	38
Feces	Total wet weight	g cap^{-1} day^{-1}	149
	Dry weight	g cap^{-1} day^{-1}	46.5
	Nitrogen	g cap^{-1} day^{-1}	2.79
	Nitrogen	% DM	6
	Protein	g cap^{-1} day^{-1}	9.7
	Lipids	g cap^{-1} day^{-1}	4.15
	Phosphorus	g cap^{-1} day^{-1}	0.81
Urine	Total wet weight	L cap^{-1} day^{-1}	1.6
	Dry weight	g cap^{-1} day^{-1}	60.5
	Nitrogen	g cap^{-1} day^{-1}	11.00
	Nitrogen	mg L^{-1}	8858.33
	Nitrogen	% DM	16
	Phosphorus	g cap^{-1} day^{-1}	0.85
	Phosphorus	mg L^{-1}	1200
	Phosphorus	% DM	3.7
Total	Total wet weight	L cap^{-1} day^{-1}	1749
	Total dry weight	g cap^{-1} day^{-1}	107
	Average TN	g cap^{-1} day^{-1}	13.79
	Average TP	g cap^{-1} day^{-1}	1.67

Table A5: Population food purchasing data used to calculate LCA and grocery import offsets by poultry and produce actors.

Food per day	kg $cap^{-1}day^{-1}$	kg cap^{-1} day^{-1}	% of total	% N
Meat	115.1	0.32	14.64	3.75
Milk	252.9	0.71	32.16	2.03
Eggs	13.7	0.04	1.74	2.03
Fish/seafood	21.7	0.06	2.76	3.18
Cereals	105.3	0.30	13.39	1.45
Starchy roots	62	0.17	7.88	1.4
Vegetables	113.2	0.32	14.39	0.47
Nuts	2.2	0.01	0.28	2.6
Fruits	100.3	0.28	12.75	0.16
kg N from meats	5.34		84.50	
kg N from fruits & vegetables	0.69		10.90	
N from eggs	0.28		4.39	

[1] (FAO 2011, USDA 2015)

Table A6: Selected waste and consumption patterns for North America.

	Agricultural Production	Handling and Storage	Processing and Packaging	Distribution: Supermarket Retail	Consumption**	Diet (%)[2]	At Home (%)[3]	Out (%)[3]
cereals	2	2	11	2	27	13	71	29
roots and tubers	20	10	15	7	30	8	53	47
oilseeds and pulses	12	0	5	1	4	<1	71	29
fruits and vegetables	20	4	2	12	28	27	75	25
meat	3.5	1	5	4	11	15	62	38
fish and seafood	12	0.5	6	9	33	3	62	38
milk	3.5	0.5	1	0.5	15	32	82	18
total weighted value*	3	2	2	10	21	100	68	32

***calculated based on percent of diet**
****includes home and out of home consumption**

[1] (FAO 2011)
[2] (Nations 1977, Cease, Capps et al. 2015)
(Agriculture 2012)

A.2.2 Calculated Food Flows

Table A 7: Assumptions and constants for food flow calculations.

Abbreviation	Unit	Meaning	Value
FN_{food}	g N day^{-1}	Per capita food nitrogen consumption rate	13.72 [1,3,4]
$ff_{child\text{-}food}$	%	Fraction of food N assimilated by a child	0.7 [1,2]
$ff_{adult\text{-}food}$	%	Fraction of food N assimilated by an adult	0 [1]
ff_{WR}	%	Fraction of food wasted at residence or restaurant	20.9[6]
ff_{WG}	%	Fraction of food wasted by grocery	9.8[6]
ff_{out}	%	Fraction of food eaten at restaurants (eaten out)	32[7]
ff_{in}	%	Fraction of food consumed at residence (eaten in)	68[7]
$f_{grinder}$	%	Fraction of households with kitchen grinder	2.3[5]
TP	number	Total population in zone	varied
YP	number	Total youth population in zone	varied
N_{urine}	kg N day^{-1}	Total population N from urine to wastewater	calculated
N_{feces}	kg N day^{-1}	Total population N from feces to wastewater	calculated
FW	g N day^{-1}	Food waste rate per capita	calculated
N_{food}	kg N day^{-1}	Total food consumed (out + in)	calculated
$N_{food\text{-}restaurant}$	kg N day^{-1}	Total food inputs to Restaurant	calculated
$N_{food\text{-}grocery}$	kg N day^{-1}	Total food inputs to zone grocery	calculated
N_{WW}	kg N day^{-1}	Total zone wastewater nitrogen	calculated
N_{MSW}	kg N day^{-1}	Total zone nitrogen to municipal solid waste actor	calculated

[1] (Cease, Capps et al. 2015)
[2] (USDA 2015)
[3] (Rose, Parker et al. 2015)
[4] (Wielemaker, Weijma et al. 2018)
[5] (Lundie and Peters 2005)
6 (Gunders 2012)
7 (USDA 2012)

Below, calculated food inputs for each zone, along with county totals and region totals.

Table A 8: Total food requirements calculated for each zone (for purchase), county totals and region totals.

Zone No.	County No.	County	Nitrogen required from meat (or protein substitute) (kg N)	Nitrogen requirement from produce (kg N)	Nitrogen requirement from eggs (kg N)
1	7	**Bartow**	34763.15	4498.76	1635.91
2	7		17381.57	2249.38	817.96
3	7		521453.17	67482.17	24538.97
4	7		3476.31	449.88	163.59
5	7		3476.31	449.88	163.59
6	7		15643.42	2024.44	736.16
7	7	**Total**	**596194.00**	**77155.00**	**28056.00**
8	13	**Cherokee**	291635.43	37741.06	13724.02
9	13		364548.75	47176.90	17155.24
10	13		145820.69	18870.91	6862.15
11	13		291635.43	37741.06	13724.02
12	13		182274.37	23588.45	8577.62
13	13	**Total**	**1275914.66**	**165118.37**	**60043.04**
14	18	**Clayton**	296278.45	38341.92	13942.52
15	18		781099.35	101083.45	36757.62
16	18		269342.96	34856.15	12674.96
17	18		197518.97	25561.28	9295.01
18	18	**Total**	**1544239.73**	**199842.79**	**72670.11**
19	23	**Cobb**	731401.15	94651.91	34418.88
20	23		438843.07	56791.46	20651.44
21	23		1462802.30	189303.83	68837.76
22	23		1462802.30	189303.83	68837.76
23	23	**Total**	**4095848.82**	**530051.02**	**192745.83**
24	33		333250.01	43126.47	15682.35
25	33	**Cowetta**	83312.50	10781.62	3920.59
26	33		2553.66	330.47	120.17
27	33		6666.91	862.78	313.74
28	33		11107.54	1437.45	522.71
29	33		222168.66	28751.24	10455.00
30	33		16661.31	2156.17	784.06
31	33		13327.86	1724.78	627.19

Table A8 (Continued)

32	33		54430.52	7043.95	2561.44
33	33	**Total**	**743478.96**	**96214.92**	**34987.25**
34	36	**DeKalb**	1470915.68	190353.79	69219.56
35	36		2647642.28	342636.06	124594.93
36	36	**Total**	**4118557.96**	**532989.85**	**193814.49**
37	47		384144.69	49712.84	18077.40
38	47	**Douglas**	2559.62	331.24	120.45
39	47		38412.09	4970.98	1807.63
40	47		192072.34	24856.42	9038.70
41	47		33292.86	4308.49	1566.72
42	47		137653.73	17814.01	6477.82
43	47	**Total**	**788135.32**	**101993.98**	**37088.72**
44	47	**Fayette**	288343.64	37315.06	13569.11
45	47		230674.91	29852.05	10855.29
46	47		115337.46	14926.02	5427.65
47	47	**Total**	**634356.01**	**82093.13**	**29852.05**
48	57	**Forsyth**	871912.13	112835.69	41031.16
49	57		11988.52	1551.46	564.17
50	57		59942.62	7757.28	2820.83
51	57		190733.01	24683.10	8975.67
52	57		54496.00	7052.42	2564.52
53	57		82830.34	10719.22	3897.90
54	57		108991.99	14104.85	5129.03
55	57		136237.01	17630.67	6411.15
56	57		10899.20	1410.48	512.90
57	57	**Total**	**1528030.82**	**197745.17**	**71907.33**
58	67	**Fulton**	319713.81	41374.73	15045.36
59	67		511536.15	66198.80	24072.29
60	67		2131.03	275.78	100.28
61	67		106569.29	13791.32	5015.03
62	67		21316.24	2758.57	1003.12
63	67		511536.15	66198.80	24072.29
64	67		2131403.58	275828.70	100301.35
65	67		852560.24	110331.33	40120.48
66	67		1023072.29	132397.59	48144.58
67	67	**Total**	**5479838.77**	**709155.61**	**257874.77**
68	74	**Gwinnett**	1912717.19	247528.11	90010.22
69	74		956361.57	123764.44	45005.25
70	74		765086.88	99011.24	36004.09
71	74		1051995.94	136140.65	49505.69
72	74		95634.37	12376.21	4500.44

Table A8 (Continued)

73	74		11952.81	1546.83	562.49
74	74	**Total**	**4793748.77**	**620367.49**	**225588.18**
75	81	**Hall**	674286.01	87260.54	31731.11
76	81		280950.52	36358.30	13221.20
77	81		22476.99	2908.79	1057.74
78	81		28655.79	3708.40	1348.51
79	81		42144.36	5453.98	1983.26
80	81		21072.18	2726.99	991.63
81	81	**Total**	**1069585.86**	**138416.99**	**50333.45**
82	89	**Henry**	86705.48	11220.71	4080.26
83	89		104045.39	13464.70	4896.25
84	89		554906.74	71811.46	26113.26
85	89		104045.39	13464.70	4896.25
86	89		138725.20	17952.67	6528.24
87	89		121385.29	15708.68	5712.25
88	89		104045.39	13464.70	4896.25
89	89	**Total**	**1213858.87**	**157087.62**	**57122.77**
90	96	**Paulding**	200661.94	25968.02	9442.91
91	96		133772.64	17311.75	6295.18
92	96		138189.46	17883.34	6503.03
93	96		200661.94	25968.02	9442.91
94	96		133772.64	17311.75	6295.18
95	96		40132.39	5193.60	1888.58
96	96	**Total**	**847191.00**	**109636.48**	**39867.81**
97	102	**Rockdale**	397067.77	51385.24	18685.54
98	102		62043.88	8029.21	2919.71
99	102		14887.44	1926.61	700.59
100	102		10917.06	1412.80	513.74
101	102		22334.13	2890.30	1051.02
102	102	**Total**	**507250.28**	**65644.15**	**23870.60**
103	103	**Region Total**	**29236229.78**	**3783512.09**	**1375822.58**

A.3 Poultry

A.3.1 Supporting Poultry Documentation

Table A 9: Poultry feed minimum nutrient requirements for meat and laying chickens.

	Broilers	**Layers**
Crude protein (%)	20.3	15
Fatty acids (%)	1	1
non-phytate P (%)	0.37	0.15
Metabolizable energy (kcal kg^{-1})	3200	2900
Dry matter (kg $kg^{-1} d^{-1}$)[1]	0.075	0.042
Total feed per chicken (g d^{-1})[1]	73	86
N content (g N d^{-1})[2]	2.4	2.1

[1] (Ravindran 2013)
[2] (National Research Council 1987)
[3] (WHO/FAO 2002)

A.3.2 Calculated Poultry Nitrogen Flows

Table A 10: Calculated poultry flows per county per year.

County	Total inventory [1] (no. chickens)*	Eggs (no. per year)**	Eggs[2] (kg N yr^{-1})	Feed imports [3] (kg N yr^{-1})	Biomass [4] (kg N year^{-1})	Mortality biomass[5] (kg N year^{-1})	Meat (kg N year^{-1})[5]	Manure[3] (kg N year^{-1})	Manure volatilization[6] (kg N year^{-1})
Bartow	3,576,791	24,047,660	19,527	3,106,231	1,533,589	61,344	912,792	1,553,115	543,590
Cherokee	874,877	13,439,300	10,913	757,341	367,758	14,710	218,890	378,671	132,535
Clayton	86	31,390	25	65	7	0	4	32	11
Cobb	1,252	420,480	341	954.39	136	5	81	477.19	167
Coweta	1,906	695,690	565	1,435.00	153	6	91	718	251
DeKalb	0	0	0	0.00	0	0	0	0	0
Douglas	154	56,210	46	115.94	12	0	7	58	20
Fayette	299	109,135	89	225.11	24	1	14	112.56	39.39
Forsyth	2,113,001	89,972,865	73,058	1,810,578	832,232	33,289	495,344	905,289	316,851
Fulton	5,049	1,842,885	1,496	3,801.32	404	16	241	1,900	665
Gwinnett	223,106	75,190	61	194,214	97,046	3,882	57,762	97,107	33,987
Hall	5,663,650	585,157,780	475,148	4,742,094	1,895,899	75,836	1,128,439	2,371,047	829,866
Henry	1,787	285,065	231	1,464	500	20	298	732	256
Paulding	870,247	133,955	109	757,602	378,692	15,148	225,398	378,801	132,580
Rockdale	1,025	358,430	291	776.77	97	4	58	388	136
Total:	**13,333,230**	**716,626,035**	**581,900**	**11,376,898**	**5,106,549**	**204,262**	**3,039,418**	**5,688,449**	**1,990,957**

*** Layers + Broilers**
****1 egg per layer per day**
[1](USDA 2014)
[2] (USDA 2015)
[3] (Ravindran 2013)
[4] (NRC 1987)
[5] (Ritz and Merka 2013)
[6] (Cabrera and Gordillo 1995)

A.4 Cropland and Produce

A.4.1 Estimation of Crop Nitrogen Totals

Table A 11: Crop totals and nitrogen yield calculated for most common North Georgia crops (USDA 2014).

Principal field crops

	Average yield per acre	Yield per acre (kg)	Planted area (1000 acres)	Planted are (acres)	Harvested area (1000 acres)	Harvested area (acres)	Weighting factor	Weighted yield (kg)	N (kg/kg)	Weighted N
Corn (bushels)	125.38	3184.53	338.75	338750.00	286.88	286875.00	0.10	325.93	0.0145	4.74
Cotton (lbs.)	745.86	338.31	1265.00	1265000.00	1283.57	1283571.43	0.46	154.93	0.0145	2.25
Hay (tons)	2.50	2267.96	636.25	636250.00	636.25	636250.00	0.23	514.81	0.0047	2.43
Oats (bushels)	58.63	851.24	82.50	82500.00	27.50	27500.00	0.01	8.35	0.0145	0.12
Rye (bushels)	23.00	584.20	248.75	248750.00	34.38	34375.00	0.01	7.16	0.0145	0.10
Sorghum (bushels)	46.00	1043.28	51.25	51250.00	32.50	32500.00	0.01	12.10	0.0145	0.18
Tobacco (lbs.)	2055.63	932.42	21.26	21262.50	21.26	21262.50	0.01	7.07	0.0047	0.03
Wheat (bushels)	47.88	1303.16	336.25	336250.00	336.25	336250.00	0.12	156.33	0.0145	2.27
			Total field cropland:	**2980012.50**	**2658.58**	**2658583.93**	**0.95**			

Fruits and vegetables

	Average yield per acre	Yield per acre (kg)	Planted area (1000 acres)	Planted are (acres)	Harvested area (1000 acres)	Harvested area (acres)	Weighting factor	Weighted yield (kg)	N (kg/kg)	Weighted N
Onions (cwt)	232.50	11811.53	13.96	13962.50	12.06	12062.50	0.00	50.83	0.0047	0.24
Tomato (cwt)	304.38	15462.95	5.45	5450.00	5.20	5200.00	0.00	28.69	0.0047	0.14
Sweet corn (cwt)	132.50	6731.30	26.88	26875.00	25.00	25000.00	0.01	60.04	0.0047	0.28
Watermelon (cwt)	232.14	11793.39	25.74	25742.86	23.29	23285.71	0.01	97.98	0.0016	0.15
Peach (tons)	3.86	196.02	NA	NA	11.43	11428.57	0.00	0.80	0.0016	0.00
Apple (lbs.)	2267.85	115211.85	NA	NA	1.14	1142.86	0.00	46.98	0.0016	0.07
Blueberry (lbs.)	3822.86	194209.94	NA	NA	5.17	5171.43	0.00	358.32	0.0016	0.56
Grape (tons)	2.79	141.59	NA	NA	1.12	1116.67	0.00	0.06	0.0016	0.00
Bean, snap (cwt)	47.29	2402.22	18.81	18812.50	17.00	17000.00	0.01	14.57	0.0047	0.07
Cabbage	262.86	13353.75	10.61	10614.29	9.29	9285.71	0.00	44.24	0.0047	0.21
Cantaloupe	188.57	9579.86	5.94	5942.86	5.67	5671.43	0.00	19.38	0.0047	0.09
Carrot	295.00	14986.68	3.10	3100.00	3.00	3000.00	0.00	16.04	0.0047	0.08
Cucumber	177.86	9035.55	12.36	12362.50	13.00	13000.00	0.00	41.91	0.0047	0.20
Pepper, bell	230.00	11684.53	4.42	4416.67	4.11	4114.29	0.00	17.15	0.0047	0.08

Table A11 (Continued)

Squash	130.71	6640.59	8.61	8614.29	7.87	7871.43	0.00	18.65	0.0047	0.09
Total fruit and vegetable cropland planted:				**135893.45**	**144.4**	**144350.60**	**0.05**			
Total cropland planted:				**3115905.95**						
Total cropland harvested:				**2802934.52**						
Cropland average yield (kg/acre):				**2002.31**						
Cropland average N in food (kg/acre):				**14.39**						

A.4.2 Calculated Cropland Nitrogen Flows

Table A 12: Calculated values for nitrogen fertilizer application, uptake and volatilization, and crop and stover yield for each of the 15 counties (County Urban Farm or sum of Zone Urban Farms) and region totals (Region Urban Farm case), alongside population data.

		Cropland fertilized (using chemical fertilizer)					
County	**Population as of 2010 [1]**	**Acres [2]**	**kg N applied**	**Crop estimate* (kg N y^{-1})**	**Uptake (40%) (kg N y^{-1})**	**Stover estimate (kg year^{-1})**	**Volatized (kg N y^{-1})**
Bartow	100,157	10,169	828,774	146,434	308,304	161,870	58,014
Cherokee	214,346	574	46,781	8,266	17,403	9,136.93	3,275
Clayton	259,424	88	7,172	1,267	2,668	1,400.78	502
Cobb	688,078	61	4,972	878	1,849	971.00	348
Coweta	124,900	2,436	198,534	35,078	73,855	38,776.25	13,897
DeKalb	691,893	4	326	58	121	63.67	23
Douglas	132,403	1,121	91,362	16,142	33,986	17,844	6,395
Fayette	106,567	621	50,612	8,942	18,827	9,885	3,543
Forsyth	256,700	7,886	642,709	113,558	239,088	125,529.35	44,990
Fulton	920,581	1,005	81,908	14,472	30,470	15,997.59	5,734
Gwinnett	805,321	708	57,702	10,195	21,465	11,269.94	4,039
Hall	179,684	3,514	286,391	50,602	106,537	55,935.85	20,047
Henry	203,922	1,567	127,711	22,565	47,508	24,943.51	8,940
Paulding	142,324	478	38,957	6,883	14,492	7,608.80	2,727
Rockdale	85,215	237	19,316	3,413	7,185	3,772.57	1,352
Total Flow:	**4,911,515**	**30,469**	**2,483,224**	**438,754**	**923,759**	**485,006**	**173,826**

***Weighted crop yield nitrogen per acre calculation can be found in Table A8**

[1] (USDA 2014)

[2] (Atlanta Regional Commission Research 2010)

APPENDIX B. NUTRIENT CYCLING MODULE EXPERIMENT SUPPORTING DATA AND SELECTED FLOW TABLES

B.1 Black Soldier Fly Larvae

B.1.1 Supporting Black Soldier Fly Documentation

The following tables (B1 and B2) provide details used to estimate black soldier fly larvae growth rates and nitrogen conversion efficiencies for the Nutrient Optimizing Module case study.

Table B1 outlines experimental data collected regarding feeding rates and black soldier fly larvae yield reared on fresh human feces. Banks, Gibson et al. (2014) use two feeding regimes, FR1 and FR2 in which they employ incremental feeding or lump sum feeding, respectively. Each feeding regime is split up into three groups (A, B, and C) with different larval density (1, 10, or 100 larvae per treatment, respectively). Equal quantities of feces, without larvae, served as their control.

Table B1: Black Soldier Fly Larvae growth, fed on human feces (Banks, Gibson et al. 2014). Group A contained 1 larva, B contained 10 larvae, and C contained 100. FR1 was continuous feeding, and FR2 was lump sum feeding.

Group	Feeding regime	Prepupal weight (g)	Feed added (g)	Mean feed added (g)	Bioconversion (%)	Feed consumed (g)	FCR	Prepupal wet weight mean (g)	Pupation (%)	Residue (wet weight)	Residue (wet weight) Mean (g)	Waste reduction (wet weight) mean (%)
A	1	8.5	390.3	9.8 +/- 0.23	2.2	130.1	15.2	0.2258 +/- 0.0078	92.5	260.2	6.5 +/- 0.2	33.4 +/- 1.44
	2	11.3	481.5	12.0 +/- 0.04	2.3	121.2	10.7	0.3151 +/- 0.0012	87.5	360.3	9 +/- 0.1	25.2 +/- 0.8
B	1	65.3	436.5	10.9 +/- 0.08	14.9	216.7	3.3	0.1936 +/- 0.0026	82.8	219.8	5.5 +/- 0.12	49.7 +/- 1.03
	2	110.7	482.5	12.1 +/- 0.04	22.9	221.1	2	0.2986 +/- 0.0039	92.5	261.4	6.5 +/- 0.9	45.8 +/- 0.73
C	1	104.8	658.1	109.7 +/- 1.43	15.8	357	3.4	0.1998 +/- 0.0034	85	301.1	50.2 +/- 0.81	54.2 +/- 0.86
	2	11.6	720.5	120.1 +/- 0.08	1.6	393.4	33.9	0.2410 +/- 0.0098	8.2	327.1	54.5 +/- 2.67	54.6 +/- 2.2

Table B2 outlines experimental results for food waste conversion by 4 insect species (cockroaches, black soldier flies, yellow mealworms, and crickets). Results demonstrated that diet affected survival in all species but black soldier flies (BSF), which was a deciding factor leading to their use BSF in this thesis.

Table B 2: Average survival rate (%), development time (days), Feed Conversion Ratio (FCR), Dry matter conversion of ingested food (%), and nitrogen efficiency (%), of Argentinean cockroach, black soldier fly, yellow mealworm, and house cricket (Oonincx, van Broekhoven et al. 2015).

		Survival rate mean (%)	SD (+/-)	Development time (days)	SD (+/-)	FCR mean	SD (+/-)	DM conversion of ingested food (%)	SD (+/-)	N efficiency (%)	SD (+/-)	DM (%)	SD (+/-)	CP (% DM)	SD (+/-)	N (% DM) calc.*
Cockroach	**average:**	61.20	16.26	241.60	25.04	1.98	0.28	19.80	2.72	63	8.64	32.82	2.48	58.88	1.32	9.42
BSF	**average:**	76.80	21.04	29.80	4.86	2.00	0.49	20.40	3.58	50	15.06	34.56	2.18	42.14	1.63	6.74
Mealworm	**average:**	65.08	8.16	135.83	13.53	6.58	0.93	12.58	1.64	35	4.16	36.33	1.86	49.65	1.23	7.94
Cricket	**average:**	21.2	8.68	101.6	4.2	5.22	1.46	7.4	2.9	32	12.1	24.74	2.60	58.5	4.175	9.36

B.1.3 Calculated Black Soldier Fly Nitrogen Flows

Table B 3: Total Black Soldier Fly (BSF) potential biomass, residue, and volatilization in each zone and county.

Zone ID/ County	BSF Potential Biomass (kg N/year)	BSF Residue (kg N/year)	BSF Volatilization (kg/year)
Equation:	*= 0.504* (WWTP solids + septage + MSW)*	*=WWTP solids + septage + MSW)-biomass-volatilization*	*= 0.1*(WWTP solids + septage + MSW)*
1	7522.13	6299.80	1102.94
2	3761.07	3149.90	551.47
3	112833.29	94498.07	16544.21
4	752.21	629.98	110.29
5	752.21	629.98	110.29
6	3384.96	2834.91	496.32
Bartow Total:	**129005.87**	**108042.63**	**18915.52**
8	63995.85	53550.48	9429.56
9	79995.79	66938.92	11787.09
10	31998.58	26775.79	4714.87
11	63995.85	53550.48	9429.56
12	39997.90	33469.46	5893.55
Cherokee Total:	**279983.95**	**234285.14**	**41254.62**
14	67748.59	56551.10	10122.12
15	178610.29	149089.56	26685.64
16	61589.38	51409.88	9201.89
17	45165.73	37700.73	6748.08
Clayton Total:	**353113.99**	**294751.27**	**52757.73**
19	167383.24	139711.40	25014.97
20	100430.49	83827.30	15009.06
21	334766.49	279422.80	50029.93
22	334766.49	279422.80	50029.93
Cobb Total:	**937346.71**	**782384.30**	**140083.89**
24	72980.00	61075.79	10745.80
25	18245.00	15268.95	2686.45
26	559.24	468.02	82.34
27	1460.02	1221.87	214.98
28	2432.49	2035.71	358.17
29	48653.77	40717.56	7163.93
30	3648.74	3053.57	537.25

Table B3 (Continued)

31	2918.73	2442.64	429.76
32	11920.00	9975.65	1755.14
Cowetta Total:	**162817.99**	**136259.75**	**23973.82**
34	338295.61	282286.60	50639.24
35	608930.73	508114.74	91150.42
DeKalb Total:	**947226.34**	**790401.34**	**141789.66**
37	85590.68	71554.50	12677.60
38	570.30	476.78	84.47
39	8558.54	7155.01	1267.68
40	42795.34	35777.25	6338.80
41	7417.93	6201.45	1098.74
42	30670.42	25640.72	4542.87
Douglas Total:	**175603.21**	**146805.71**	**26010.16**
44	63364.54	53017.57	9341.19
45	50691.64	42414.06	7472.95
46	25345.82	21207.03	3736.47
Fayette Total:	**139402.00**	**116638.66**	**20550.61**
48	190960.95	159811.29	28118.53
49	2625.65	2197.36	386.62
50	13128.27	10986.78	1933.11
51	41773.20	34959.13	6151.00
52	11935.39	9988.48	1757.46
53	18141.00	15181.83	2671.22
54	23870.77	19976.96	3514.91
55	29837.81	24970.65	4393.54
56	2387.08	1997.70	351.49
Forsyth Total:	**334660.12**	**280070.17**	**49277.88**
58	73552.39	61373.84	11011.05
59	117682.45	98197.00	17617.48
60	490.26	409.08	73.39
61	24517.01	20457.57	3670.28
62	4903.95	4091.97	734.14
63	117682.45	98197.00	17617.48
64	490344.24	409154.73	73406.27
65	196137.42	163661.66	29362.47
66	235364.91	196394.00	35234.96
Fulton Total:	**1260675.09**	**1051936.85**	**188727.52**
68	434204.19	362594.12	64717.94
69	217102.77	181297.63	32359.07
70	173681.68	145037.65	25887.18
71	238812.64	199427.05	35594.92

Table B3 (Continued)

72	21709.87	18129.42	3235.85
73	2713.40	2265.90	404.43
Gwinnett Total:	**1088224.56**	**908751.77**	**162199.39**
75	148460.74	124203.69	21900.53
76	61858.20	51751.17	9125.15
77	4948.87	4140.27	730.04
78	6309.28	5278.40	930.73
79	9279.12	7763.00	1368.83
80	4639.56	3881.50	684.42
Hall Total:	**235495.77**	**197018.05**	**34739.70**
82	18999.44	15899.74	2798.12
83	22799.06	19079.47	3357.70
84	121594.56	101756.81	17907.69
85	22799.06	19079.47	3357.70
86	30398.32	25438.93	4476.87
87	26598.69	22259.20	3917.29
88	22799.06	19079.47	3357.70
Henry Total:	**265988.19**	**222593.08**	**39173.07**
90	43230.23	36215.20	6328.83
91	28819.73	24143.11	4219.16
92	29771.28	24940.25	4358.46
93	43230.23	36215.20	6328.83
94	28819.73	24143.11	4219.16
95	8646.05	7243.04	1265.77
Paulding Total:	**182517.23**	**152899.92**	**26720.21**
97	87416.42	73133.83	12895.03
98	13659.27	11427.54	2014.92
99	3277.54	2742.04	483.48
100	2403.44	2010.75	354.54
101	4916.97	4113.61	725.32
Rockdale Total:	**111673.64**	**93427.76**	**16473.28**
Region Total:	**6603734.66**	**5516266.41**	**982647.06**

B.1.4 Redistribution Scenarios for Future Models

Table B 4: Calculation of residue redistribution according to chemical fertilizer application in each county in the Atlanta Metropolitan Region.

County	Fertilizer Required[1]	BSF Residue	Residue Remaining	Requirement Remaining	Redistributed Remainder	Residue Export
Bartow	828774	108043	0	720731	720731	0
Cherokee	46781	234285	187504	0	0	133247
Clayton	7172	294751	287579	0	0	204364
Cobb	4972	782384	777412	0	0	552458
Coweta	198534	136260	0	62274	62274	0
DeKalb	326	790401	790075	0	0	561457
Douglas	91362	146806	55444	0	0	39400
Fayette	50612	116639	66027	0	0	46921
Forsyth	642709	280070	0	362639	362639	0
Fulton	81908	1051937	970029	0	0	689338
Gwinnett	57702	908752	851050	0	0	604788
Hall	286391	197018	0	89373	89373	0
Henry	127711	222593	94882	0	0	67427
Paulding	38957	152900	113943	0	0	80972
Rockdale	19316	93428	74112	0	0	52667
Region Total:	**2483227**	**5516266**	**4268057**	**1235017**	**1235017**	**3033039**

1 (USDA 2014)

B.2 Constructed Wetlands

B.2.1 Supporting Constructed Wetlands Data

The following supporting information was used to calculate the yield and required area to support complete conversion of wastewater treatment plant (WWTP) effluent nitrogen into duckweed (*Lemna minor*) biomass.

Table B5 illustrates the role of initial biomass on the production of new biomass growth in an experimental setup involving urine as the feedstock nitrogen source for duckweed cultivation.

Table B 5: Role of initial amount of Lemna minor on the production of biomass (g), duckweed (duration of the experiment: 14 d; temperature: 24◦C; pH: 7) (Iatrou, Stasinakis et al. 2015).

Parameter	Initial Lemna minor (g)		
	0.5	**1**	**1.5**
Duckweed mass (g)	1.60 ± 0.05	3.60 ± 0.1	5.83 ± 0.35
Growth rate, *m* (1/d)	0.083 ± 0.002	0.091 ± 0.002	0.097 ± 0.04
Growth rate, *m*_area (g/ m^2d)	0.101 ± 0.003	0.227 ± 0.006	0.369 ± 0.022

Building on the information from Iatrou et al. (2015), a specific areal growth rate was estimated using the additional supporting growth rate data found in Table B6.

Table B 6: Specific areal growth rates from experimental data.

Source	Growth rate, *m*_area (g/ m^2d)
(Cheng, Landesman et al. 2002)	29
(El-Shafai, El-Gohary et al. 2007)	15.1
(Teles, Mohedano et al. 2017)	13.8
(Cheng, Landesman et al. 2002)	8.3
(Körner and Vermaat 1998)	5.5

A crude protein content of duckweed (35% of dry weight) and nitrogen content of crude protein (16% by mass) was used from experimental results drawn from literature (Körner and Vermaat 1998, USDA 2015).

B.2.2 Calculated Nitrogen Flows in Constructed Wetlands

Table B 7: Constructed wetland productivity and nitrogen county totals per year with available wastewater treatment effluent inputs.

County	Duckweed Area Requirement (m2)	Duckweed - horizontal flow area requirement (acres)	Vertical farm area equivalent Duckweed culture (acres)	Duckweed yield (kg DM/year)	Duckweed CP (kg/year)	Duckweed nitrogen (kg/year)
Bartow	142206.78	35.14	2.51	744324.51	260513.58	41682.17
Cherokee	393717.24	97.29	6.95	2060755.38	721264.38	115402.30
Clayton	803294.18	198.50	14.18	4204522.09	1471582.73	235453.24
Cobb	2147222.66	530.59	37.90	11238778.15	3933572.35	629371.58
Coweta	221891.70	54.83	3.92	1161403.36	406491.17	65038.59
DeKalb	2265963.58	559.93	40.00	11860279.97	4151097.99	664175.68
Douglas	304145.78	75.16	5.37	1591929.44	557175.30	89148.05
Fayette	200296.43	49.49	3.54	1048371.53	366930.04	58708.81
Forsyth	455896.48	112.65	8.05	2386207.77	835172.72	133627.64
Fulton	3023487.65	747.12	53.37	15825236.70	5538832.84	886213.26
Gwinnett	2311605.47	571.21	40.80	12099174.17	4234710.96	677553.75
Hall	348169.67	86.03	6.15	1822354.87	637824.21	102051.87
Henry	366073.87	90.46	6.46	1916067.24	670623.53	107299.77
Paulding	183931.69	45.45	3.25	962716.87	336950.90	53912.14
Rockdale	164861.41	40.74	2.91	862901.12	302015.39	48322.46
Total:	**13332764.60**	**3294.59**	**235.33**	**69785023.17**	**24424758.11**	**3907961.30**

B.3 Aquaponics

B.3.1 Supporting Aquaponics Data

Table B 8: Nitrogen accumulation and waste as a percent of feed (Bugbee 2004).

		Aquaponic Waste Nitrogen Fate (%)		
Biomass Accumulation	**Sludge Accumulation**	**Waste Water**	**Pant Accumulation**	**Volatilization**
45	2	2	6	45

Table B 9: Plant biomass nitrogen content, percent by mass (dry weight) (Bugbee 2004).

Leaves	Stems	Fuits	Roots
4	1.5	3	3

B.1.2 Calculated Nitrogen Flows in Aquaponics

Table B 10: Calculated aquaponic nitrogen flows for all zones (reported in kilograms of nitrogen per year).

Zone/ County ID.	AP Fish Biomass	AP Fish Sludge	APF Wastewater	AFP Volatilization	AP Plant Biomass	APF Fish Meat	APP Crop	AP Carcasses	AP Effluent
1	4479	199	5275	527	3323	2687	1662	1791	1424
2	2239	100	2637	264	1662	1344	831	896	712
3	67181	2986	79124	7912	49848	40308	24924	26872	21363
4	448	20	527	53	332	269	166	179	142
5	448	20	527	53	332	269	166	179	142
6	2015	90	2374	237	1495	1209	748	806	641
7	**76810**	**3414**	**90465**	**9046**	**56993**	**46086**	**28496**	**30724**	**24425**
8	40668	1807	47898	4790	30176	24401	15088	16267	12932
9	50836	2259	59873	5987	37720	30501	18860	20334	16166
10	20334	904	23949	2395	15088	12201	7544	8134	6466
11	40668	1807	47898	4790	30176	24401	15088	16267	12932
12	25418	1130	29937	2994	18860	15251	9430	10167	8083
13	**177924**	**7908**	**209555**	**20955**	**132019**	**106754**	**66010**	**71170**	**56580**
14	50815	2258	59849	5985	37705	30489	18852	20326	16159
15	133968	5954	157784	15778	99404	80381	49702	53587	42602
16	46195	2053	54408	5441	34277	27717	17139	18478	14690
17	33877	1506	39899	3990	25137	20326	12568	13551	10773
18	**264855**	**11771**	**311941**	**31194**	**196523**	**158913**	**98261**	**105942**	**84224**
19	125897	5595	148279	14828	93416	75538	46708	50359	40035
20	75539	3357	88968	8897	56050	45323	28025	30215	24021
21	251794	11191	296557	29656	186831	151076	93416	100718	80070
22	251794	11191	296557	29656	186831	151076	93416	100718	80070
23	**705023**	**31334**	**830361**	**83036**	**523127**	**423014**	**261564**	**282009**	**224197**
24	45960	2043	54130	5413	34102	27576	17051	18384	14615

Table B10 (Continued)

25	11490	511	13533	1353	8525	6894	4263	4596	3654
26	352	16	415	41	261	211	131	141	112
27	919	41	1083	108	682	552	341	368	292
28	1532	68	1804	180	1137	919	568	613	487
29	30640	1362	36087	3609	22735	18384	11367	12256	9744
30	2298	102	2706	271	1705	1379	852	919	731
31	1838	82	2165	216	1364	1103	682	735	585
32	7507	334	8841	884	5570	4504	2785	3003	2387
33	**102535**	**4557**	**120764**	**12076**	**76081**	**61521**	**38041**	**41014**	**32606**
34	258976	11510	305016	30502	192160	155385	96080	103590	82354
35	466155	20718	549027	54903	345887	279693	172944	186462	148237
36	**725131**	**32228**	**854043**	**85404**	**538047**	**435079**	**269024**	**290052**	**230592**
37	58069	2581	68392	6839	43087	34841	21544	23228	18466
38	387	17	456	46	287	232	144	155	123
39	5807	258	6839	684	4308	3484	2154	2323	1846
40	29035	1290	34196	3420	21544	17421	10772	11614	9233
41	5033	224	5927	593	3734	3020	1867	2013	1600
42	20808	925	24508	2451	15440	12485	7720	8323	6617
43	**119138**	**5295**	**140318**	**14032**	**88400**	**71483**	**44200**	**47655**	**37886**
44	40523	1801	47727	4773	30068	24314	15034	16209	12886
45	32418	1441	38181	3818	24054	19451	12027	12967	10309
46	16209	720	19091	1909	12027	9725	6014	6484	5154
47	**89150**	**3962**	**104999**	**10500**	**66149**	**53490**	**33075**	**35660**	**28350**
48	120245	5344	141622	14162	89222	72147	44611	48098	38238
49	1653	73	1947	195	1227	992	613	661	526
50	8267	367	9736	974	6134	4960	3067	3307	2629
51	26304	1169	30980	3098	19517	15782	9759	10522	8365
52	7516	334	8852	885	5577	4509	2788	3006	2390
53	11423	508	13454	1345	8476	6854	4238	4569	3633
54	15031	668	17703	1770	11153	9019	5577	6012	4780
55	18788	835	22128	2213	13941	11273	6970	7515	5975
56	1503	67	1770	177	1115	902	558	601	478
57	**210729**	**9366**	**248193**	**24819**	**156361**	**126438**	**78181**	**84292**	**67012**
58	56366	2505	66386	6639	41823	33819	20912	22546	17924
59	90184	4008	106217	10622	66917	54111	33458	36074	28679
60	376	17	442	44	279	225	139	150	119
61	18788	835	22128	2213	13941	11273	6970	7515	5975

Table B10 (Continued)

62	3758	167	4426	443	2788	2255	1394	1503	1195
63	90184	4008	106217	10622	66917	54111	33458	36074	28679
64	375768	16701	442571	44257	278820	225461	139410	150307	119494
65	150307	6680	177028	17703	111528	90184	55764	60123	47798
66	180368	8016	212434	21243	133833	108221	66917	72147	57357
67	**966100**	**42938**	**1137851**	**113785**	**716846**	**579660**	**358423**	**386440**	**307220**
68	317047	14091	373411	37341	235249	190228	117625	126819	100821
69	158524	7046	186706	18671	117625	95115	58812	63410	50411
70	126819	5636	149365	14936	94100	76091	47050	50728	40328
71	174376	7750	205377	20538	129387	104626	64694	69751	55452
72	15852	705	18670	1867	11762	9511	5881	6341	5041
73	1981	88	2333	233	1470	1189	735	793	630
74	**794600**	**35316**	**935863**	**93586**	**589593**	**476760**	**294797**	**317840**	**252683**
75	95758	4256	112782	11278	71053	57455	35526	38303	30451
76	39899	1773	46992	4699	29605	23939	14803	15960	12688
77	3192	142	3760	376	2369	1915	1184	1277	1015
78	4070	181	4793	479	3020	2442	1510	1628	1294
79	5985	266	7049	705	4441	3591	2220	2394	1903
80	2993	133	3525	352	2220	1796	1110	1197	952
81	**151896**	**6751**	**178900**	**17890**	**112707**	**91138**	**56354**	**60759**	**48303**
82	11999	533	14132	1413	8903	7199	4452	4799	3816
83	14398	640	16958	1696	10684	8639	5342	5759	4579
84	76791	3413	90442	9044	56979	46074	28489	30716	24419
85	14398	640	16958	1696	10684	8639	5342	5759	4579
86	19197	853	22610	2261	14245	11518	7122	7679	6105
87	16798	747	19784	1978	12464	10079	6232	6719	5342
88	14398	640	16958	1696	10684	8639	5342	5759	4579
89	**167980**	**7466**	**197843**	**19784**	**124641**	**100788**	**62320**	**67192**	**53418**
90	25200	1120	29680	2968	18698	15120	9349	10080	8014
91	16800	747	19786	1979	12465	10080	6233	6720	5342
92	17354	771	20440	2044	12877	10413	6438	6942	5519
93	25200	1120	29680	2968	18698	15120	9349	10080	8014
94	16800	747	19786	1979	12465	10080	6233	6720	5342
95	5040	224	5936	594	3740	3024	1870	2016	1603
96	**106393**	**4729**	**125308**	**12531**	**78944**	**63836**	**39472**	**42557**	**33833**
97	56359	2505	66379	6638	41818	33815	20909	22544	17922

Table B10 (Continued)

98	8806	391	10372	1037	6534	5284	3267	3523	2800
99	2113	94	2489	249	1568	1268	784	845	672
100	1550	69	1825	183	1150	930	575	620	493
101	3170	141	3734	373	2352	1902	1176	1268	1008
102	**71998**	**3200**	**84798**	**8480**	**53423**	**43199**	**26711**	**28799**	**22895**
103	**4730263**	**210234**	**5571199**	**557120**	**3509855**	**2838158**	**1754928**	**1892105**	**1504224**

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